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An implicit model development process for bounding external, seemingly intangible/non-quantifiable factors

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

DISSERTATION

AN IMPLICIT MODEL DEVELOPMENT PROCESS FOR BOUNDING EXTERNAL, SEEMINGLY INTANGIBLE/NON-QUANTIFIABLE FACTORS

by

Thomas S. Pugsley

June 2017

Dissertation Supervisor Eugene Paulo

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This research expands the modeling and simulation (M&S) body of knowledge through the development of an Implicit Model Development Process (IMDP). When augmented to traditional Model Development Processes (MDP), the IMDP enables the development of models that can address a broader array of effects than previously possible, giving users the flexibility to explore “hard-to-model” factors like space and cyber while gaining insight into their potential impacts on operational effectiveness. Specifically, the IMDP provides a formalized methodology for developing an improved model definition, where a broader, more holistic approach of defining a model’s referent is achieved. Next, the IMDP codifies the process for implementing the improved model definition within the operational model. This work serves as a proof of concept for the development of operational models that can account for and quantify External, Seemingly Intangible/Non-Quantifiable (ESINQ) factors and effects, and provides M&S users a new tool for addressing ESINQ and other “soft” factors that do not fit well into traditional MDPs. Finally, through the application of ESINQ-enabled meta-models, this work demonstrates how the improved understanding generated by the IMDP can be used to improve a set of operational and acquisitions decision support tools.

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AN IMPLICIT MODEL DEVELOPMENT PROCESS FOR BOUNDING EXTERNAL, SEEMINGLY INTANGIBLE/NON-QUANTIFIABLE FACTORS

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ABSTRACT

This research expands the modeling and simulation (M&S) body of knowledge through the development of an Implicit Model Development Process (IMDP). When augmented to traditional Model Development Processes (MDP), the IMDP enables the development of models that can address a broader array of effects than previously possible, giving users the flexibility to explore “hard-to-model” factors like space and cyber while gaining insight into their potential impacts on operational effectiveness. Specifically, the IMDP provides a formalized methodology for developing an improved model definition, where a broader, more holistic approach of defining a model’s referent is achieved. Next, the IMDP codifies the process for implementing the improved model definition within the operational model. This work serves as a proof of concept for the development of operational models that can account for and quantify External, Seemingly Intangible/Non-Quantifiable (ESINQ) factors and effects, and provides M&S users a new tool for addressing ESINQ and other “soft” factors that do not fit well into traditional MDPs. Finally, through the application of ESINQ-enabled meta-models, this work demonstrates how the improved understanding generated by the IMDP can be used to improve a set of operational and acquisitions decision support tools.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOC	Army Operating Concept
ASAT	anti-satellite
BMC2	battle management, command and control
BN	battalion
C4I	command, control, communications, computers, and intelligence
CI	confidence interval
COA	course of action
CO-ASAT	co-orbital anti-satellite
COFM	consolidation of forces model
COP	common operating picture
D3SOE	denied, degraded, and disrupted space operational environment
DE	discrete event
DOA	Department of the Army
DOD	Department of Defense
DOE	design of experiments
DP	design point
EEMM	ESINQ effects mapping matrix
ESINQ	external, seeming intangible/non-quantifiable
ExtDep	external dependencies
FA-SWN	forces analysis-system weights and normalization
FE	force equivalent
FER	force exchange ratio
FR	force ratio
FRC	force ratio calculator
GPS	global positioning system
GSR	ground sensing resolution
HAAS	high altitude atmospheric satellites
HA-HD	hasty attack – hasty defense
IDE	integrated development environment
IDO	integrated distributed operations
IMDP	implicit model development process
INCOSE	International Council on Systems Engineering
IRCPAT	improved relative combat power assessment tool
ISR	intelligence, surveillance, and reconnaissance
Lat	latency
LER	loss exchange ratio

LoB	length of battle
LOS	line of site
M&S	modeling and simulation
MBSE	model based systems engineering
MDMP	military decision making process
MDP	model development process
MOE	measure of effectiveness
MOP	measures of performance
MSSSM	M&S screening and selection methodology
NOLH	nearly orthogonal Latin hypercube
NPS	Naval Postgraduate School
NTC	National Training Center
OA	operational analysis
OC	operational concept
OE	operational environment
OEM	operational effectiveness modeling
P_c	probability of classification
P_{con}	personal concealment
P_h	probability of hit
P_k	probability of kill
PNT	position, navigation, and timing
P_v	probability of victory
RCP	relative combat power
RoF	rate of fire
R&D	research and development
SATCOM	satellite communications
SE	systems engineering
SmallSat	small satellite
SME	subject matter experts
SoS	system of systems
SysML	systems modeling language
T_d	time between detections
TSE	trade space exploration
TTP	tactics, techniques, and procedures
UCS	union of concerned scientists
UI	user interface
U.S.	United States
USG	United States Government
VV&A	verification, validation, and accreditation

EXECUTIVE SUMMARY

This dissertation introduces a new Model Development Process (MDP) that provides analysts the flexibility to represent hard-to-quantify factors and effects within operational models by taking a holistic approach to capturing a more robust set of potential contributions to a model's referent. Hard-to-quantify factors and effects have represented a significant challenge, and rather than addressing these challenges, they have for the most part been largely ignored by model developers. And, while ignoring the irrelevant aspects of the real world is paramount to the success of any MDP, in an era of unprecedented cross boundary and cross domain interoperability, the determination of the line between relevant and irrelevant must be more closely scrutinized. By moving away from considering hard-to-quantify factors and external force multipliers as non-quantifiable, and rather describing such effects as External, Seemingly Intangible/Non-Quantifiable (ESINQ), a more accurate representation of these effects can be captured by model developers, one which addresses the possibility of quantifying the impacts of these effects in the referent, while highlighting the difficulty in doing so.

This work expands the modeling and simulation (M&S) body of knowledge by formalizing a methodology to address, or bound, external dependencies and ESINQ factors and effects within the MDP. The Implicit Model Development Process (IMDP) developed in this work addresses the inefficiencies of traditional MDPs by formalizing a methodology for developing an improved model definition, where a broader more holistic approach of defining a model's referent is codified. When augmented with traditional MDPs, the IMDP enables the development of models that can address a broader array of effects than previously possible, giving users the flexibility to explore "hard-to-model" and other "soft" factors like space and cyber that do not fit well into traditional MDPs, while gaining insight into their potential impacts on operational effectiveness. By providing a methodology that allows users to bound ESINQ effects within a model, a better and more complete representation of the Operational Environment (OE) is possible, which in turn yields improved models, analysis, and decisions based on that improved understanding.

The fundamental issue with traditional MDPs is the inherent flaws in the underlying assumptions and methods for gathering data during the model definition steps, specifically during the development of the referents. Most traditional MDPs underwhelm the model definition step, devoting a relatively small portion of the overall resource budget to this critical step, often assuming the user will ensure an adequate understanding of the OE is instantiated in the referent prior to model development. Thus, the model definition step, for the most part, has been un-formalized, weakly defined, and lacking any specific detail of how to conduct model definition, offering just a simple framework or best practices for users. Models developed using traditional MDPs are primarily informed by just two contributing sources, internal contributors, which captures the key explicit system characteristics and effects that the modeler is interested in representing, and external contributors, which bound unknown contextual effects of interest like environmental effects, typically seen as distractors, degraders, or noise. Unfortunately, in the OE of today, where modern systems tend to rely heavily on the contributions from external force multipliers like space-based systems for the generation of internal combat power, this two-contribution approach to model development ignores a sizeable portion of the actual OE, where many ESINQ systems and effects reside. This author believes that the primary reason for the inability of traditional MDPs to capture an accurate assessment of the OE during model definition is their failure to recognize the existence of more than two sources of combat power in developing the referent.

While current MDPs and Model Based Systems Engineering (MBSE) analysis methodologies support the development of accurate models and system definitions, neither can adequately address ESINQ factors and their impacts. In an age when network-centric operations of highly technical systems has become the standard, little has been done to fully understand or capture the dependencies that modern systems have on ESINQ factors to generate internal metrics of system effectiveness. Simply put, as modern systems continue to evolve increased dependencies on external elements, our understanding of those systems will continue to diverge from the ground truth because we cannot accurately attribute or quantify the impacts of those external elements. This incomplete understanding of the OE is then passed on to the model development step,

which relies on the quality of the model definition step. Thus, current MDPs produce models that are more wrong than they could/should be, and unfortunately, as the dependencies of modern systems on external support continue to rise, so will the inaccuracies of traditional models. The problem is further complicated by the fact that most traditional MDPs take a purely explicit model development approach, directing users to avoid hard-to-quantify input sources for fear of injecting subjectivity into the study. Thus, most traditional MDPs are ill-equipped to model effects that can be considered ESINQ, resulting in the majority of such factors and effects being ignored.

In order to account for these external and ESINQ contributions, which are often subjective and difficult to quantify, users of traditional MDPs must acknowledge that not only do additional referent contributors exist, but also that they can be significant. By breaking away from the inflexible, closed-system approach of traditional MDPs, it should be possible to capture a more accurate representation of the OE in the referent. The IMDP complements traditional MDPs by formalizing a methodology for expanding the model definition step to account for external dependencies and ESINQ effects of interest in the referent. By focusing on improving the underlying MDPs to account for ESINQ force multipliers during model development, it should be possible to produce better models, execute better Operational Analysis (OA), create better decision support tools, and thus, make better and more informed decisions.

This work demonstrates how the IMDP can be used to improve model definition and development, the two primary steps of most traditional MDPs, enabling users to (1) account for the external dependencies and ESINQ factors and effects that currently go unaddressed and (2) gain novel insights into the workings of the model. The IMDP expands traditional MDPs by formalizing a methodology to execute a more complete MDP, specifically with regard to expanding and improving the level of guidance and detail of the model definition step. Through the use of the IMDP, a more accurate representation of the actual OE can be implemented in the model, greatly improving the model’s fidelity and ability to link a system’s characteristics, including inputs from external dependencies and ESINQ effects, to metrics of operational effectiveness. Figure ES-1 provides a description of how the IMDP augments traditional MDPs.

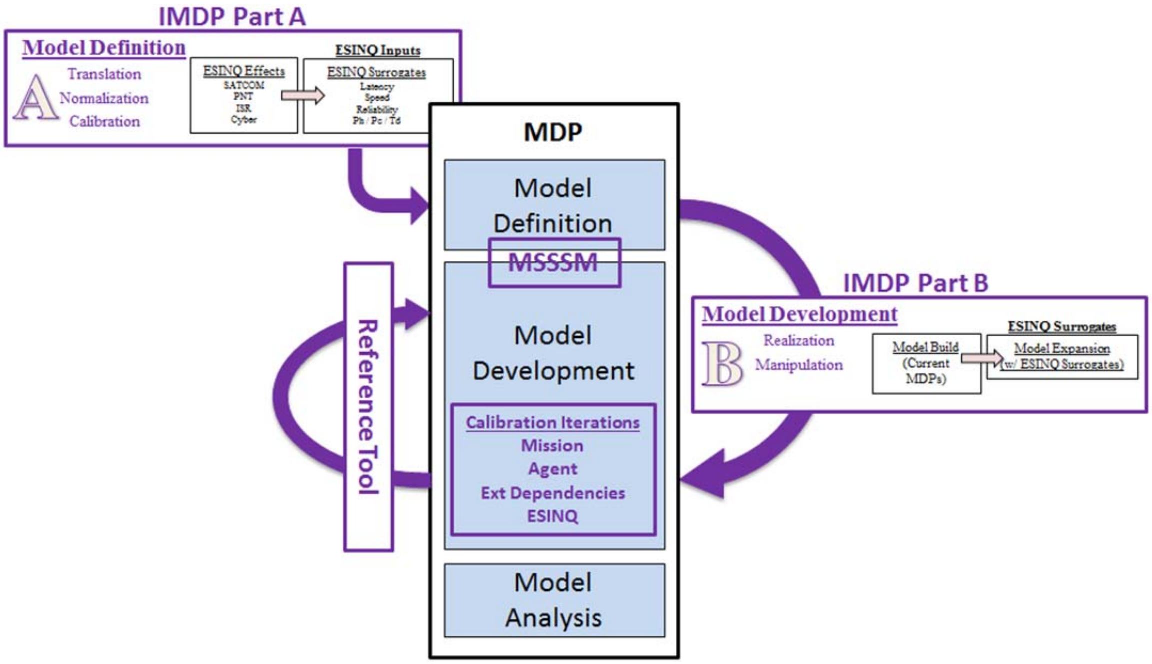

Figure ES-1. MDP

For consistency with traditional MDPs, the author has broken the IMDP in two general steps: the model definition step (part A: decomposition); and the model development step (part B: integration). Part A of the IMDP formalizes the process for bounding ESINQ factors by better defining the interactions of the system with the external environment during model definition. Specifically, part A puts a significant amount of emphasis into the definition of the model, which differs from traditional MDPs by providing more structure to the weakly-defined model definition step as well as the means for accounting for both external dependencies and ESINQ effects in the model referent. In this step, ESINQ factors and effects of interest are identified, translated, normalized, and then calibrated in preparation for their inclusion within the model through an implicit modeling technique that utilizes surrogate factors. Part B of the IMDP formalizes the process for iteratively implementing the improved referent developed in part A using surrogate factors, and enables the calibration and modeling of external dependencies and ESINQ effects. Specifically, part B manipulates surrogate factors within the model to generate a range of responses that can be used to bound the impacts of these ESINQ effects on measures of operational effectiveness. It is the bounding of

these responses that is of significance to this work because it facilitates the development of meta-models capable of representing the impacts of ESINQ effects of interest on measures of operational effectiveness.

While a standalone process from the IMDP, this work also provides a formalized methodology for screening and selecting an appropriate M&S package, which guides the user to the selection of a more appropriate M&S package, a step typically ignored in traditional MDPs. The combination of these three improvements to current MDPs allows for a more complete understanding of the system, to include external dependencies and ESINQ effects and their interactions with the environment within the model, as well as a more complete investigation of the system trade-space. By developing a methodology that can more accurately address ESINQ effects within a model, it will be possible to capture a more holistic understanding of the OE. By making operational and acquisitions decisions based on the performance of competing emerging systems and strategies within this more holistic understanding of the actual OE, we greatly increase the chances for success by producing a more robust system with direct traceability to metrics of operational effectiveness.

The primary outcome from the execution of the IMDP was the development of meta-models that can quantify the impacts from ESINQ effects on metrics of operational effectiveness. These meta-models have a nearly limitless capacity to inform and to improve other tools: yet for the most part, the application of such outcomes has remained mostly unformalized. Differing from other MDPs, the IMDP puts a more formal effort into the utilization of these meta-models for use within external tools, specifically in the development of ESINQ-enabled operational and acquisitions decision support tools, a focal point of this dissertation. In this work, we show how the ESINQ-enabled meta-models can be applied to other tools to improve their ability to capture a more accurate representation of the OE. Two such examples are given, the first of which was the development of the Improved Relative Combat Power Assessment Tool (IRCPAT) which can be seen in Figure ES-2.

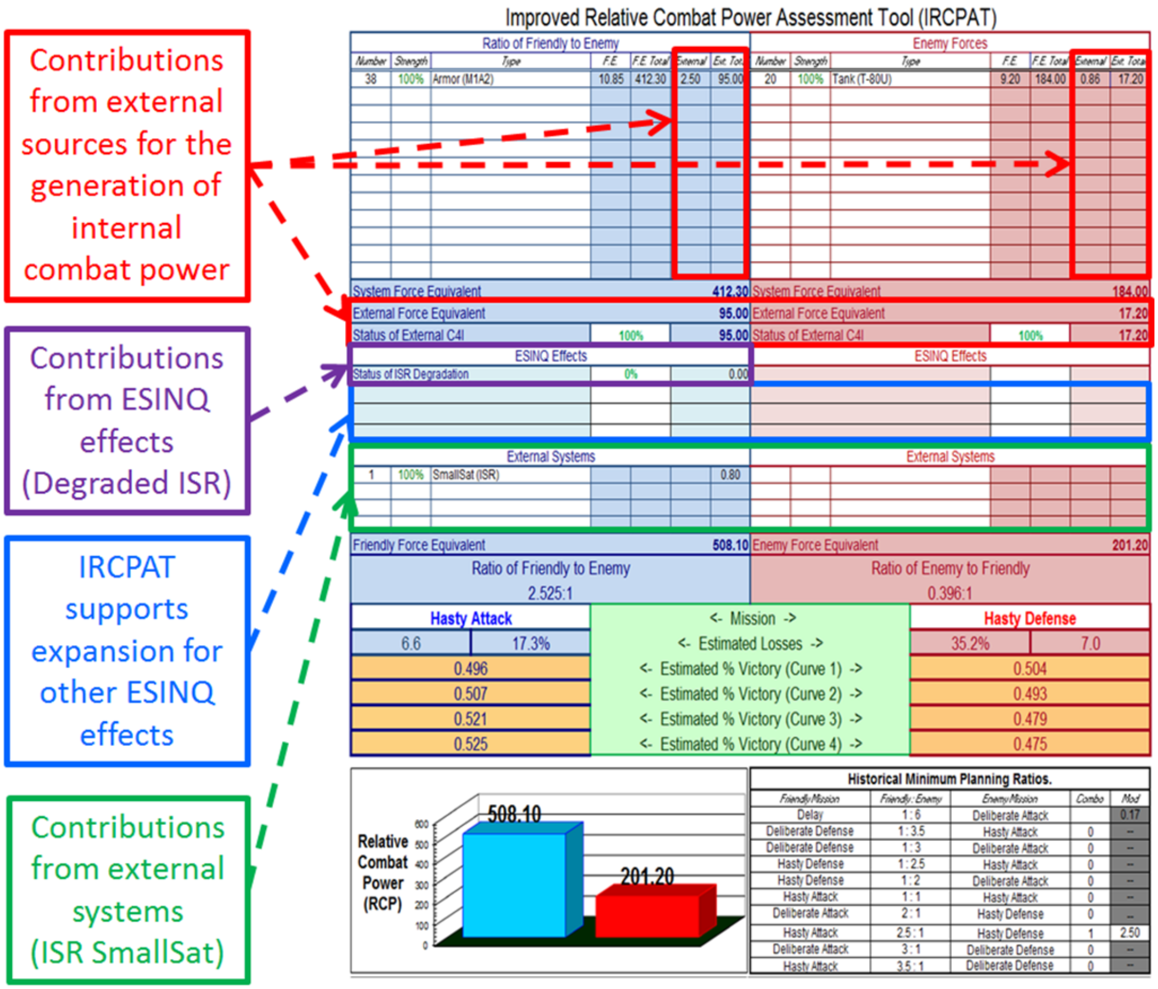

Figure ES-2. IRCPAT

The IRCPAT shown here has been instantiated to include the degraded Intelligence, Surveillance, and Reconnaissance (ISR) meta-model developed during the execution of the IMDP in Chapter IV, specifically formatted to provide a degradation factor with respect to Relative Combat Power (RCP). The IRCPAT is unique in that neither external dependencies nor ESINQ contributors to combat power were previously accounted for in modern operational decision support tools. Thus, the IRCPAT fills significant gaps in modern operational decision support tools by accounting for the contributions of external dependencies, ESINQ effects, and external systems on the generation of combat power, and facilitates a more detailed and complete analysis of the RCP of opposing forces. By improving its accuracy, usability, and relevance, the

IRCPAT will be far more useful than current tools, and will have immediate relevance to operational planners Army-wide.

The second example used in this work demonstrated the application of the outcomes of the IMDP to support the development of an ESINQ-enabled acquisition support tool. The power of acquisitions decision support tools to effectively link operational and synthesis models is clearly articulated in modern works, and provides users extremely flexible Trade Space Exploration (TSE) tools for investigating system design considerations and the resulting impacts to operational effectiveness. By applying the outcomes of the IMDP, specifically through the integration of the ESINQ-enabled meta-models, a more complete TSE tool was developed. This expansion gave TSE tools more utility for the user and allowed for a more accurate assessment of not only the operational impacts from degradation, but the potential of emerging systems to mitigate these impacts. The JMP TSE tool developed in this work can be seen in Figure ES-3.

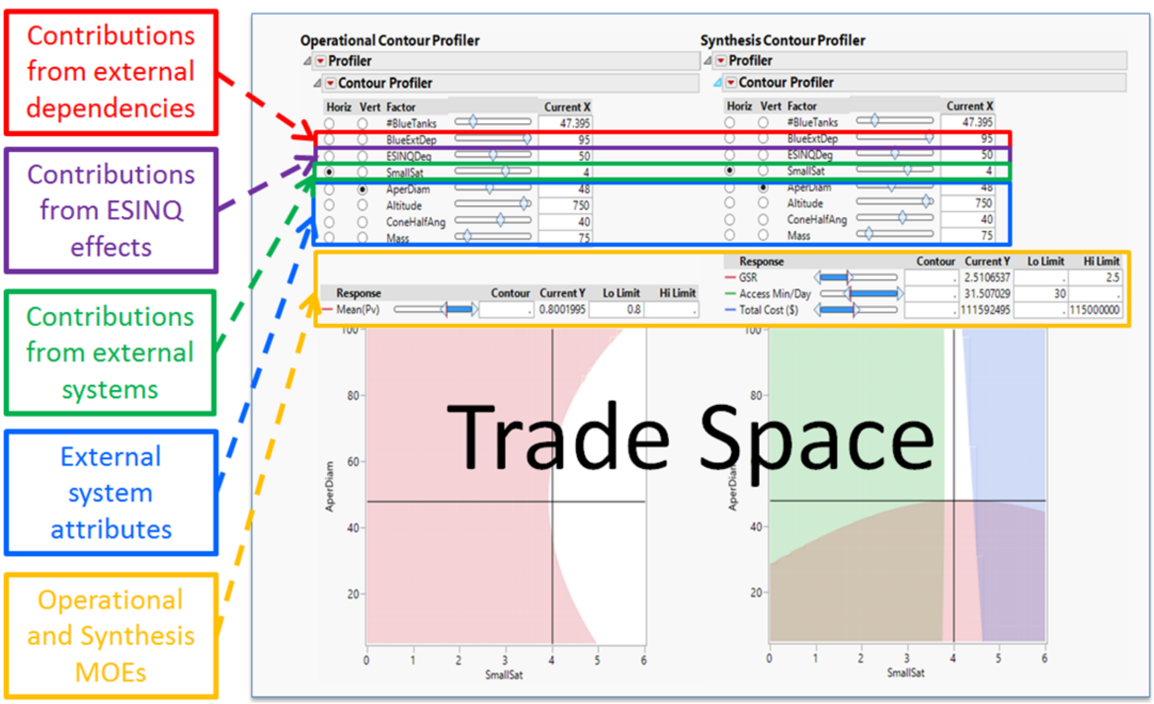

Figure ES-3. TSE Tool

By using an ESINQ-enabled operational model in conjunction with a linked synthesis model, the resulting TSE tool can account for the external dependencies and ESINQ effects previously ignored in other tools, and thus, capture a more inclusive and accurate representation of the OE during analysis. By expanding the TSE tool using ESINQ-enabled models, we allow for the assessment of ESINQ effects. Thus, users can better assess ESINQ-based systems whose contributions are measured in terms of ESINQ effects, like SmallSats, something that has been difficult to do using traditional MDPs. When used to assess the feasibility and impact of emerging ESINQ-based systems, this improved TSE tool fills known gaps within the acquisitions community and provides users with a more detailed and complete analysis of the impact that design choices will have on metrics of operational effectiveness. This improvement of current TSE tools through the use of ESINQ-enabled models will have immediate operational relevance to acquisitions planners, and should provide them a more robust capability to evaluate design decisions regarding emerging ESINQ systems.

The ability of the IMDP to support the development of better models facilitates the secondary contributions of this work. When these models are used as foundational elements in other decision support tools, the overall accuracy of these tools is improved. This improvement is largely due to the underlying models' increased accuracy at representing the OE and their ability to account for a larger number of potential contributions to RCP, specifically through addressing the external dependencies and ESINQ effects so routinely ignored in traditional MDPs. The IMDP presented in this work gives users the ability to loosely quantify or "bound" the impacts from ESINQ factors and effects on measures of operational effectiveness. Thus, it becomes possible to conduct quantifiable system analysis capable of assessing the contributions of ESINQ factors and effects (like space-based capabilities) to friendly combat power. By following the IMDP presented in this work, a better evaluation of the OE can be made, which will allow for more informed operational and acquisition decisions regarding the allocation of resources, which will, in turn, greatly improve the OA activities of the M&S community at large.

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And finally to all those who came before, who braved the dark waters and struggled to bring light to the world, without your work and effort we would all be lost.

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I. INTRODUCTION

> To rely on rustics and not prepare is the greatest of crimes; to be prepared beforehand for any contingency is the greatest of virtues.
>
> —Sun Tzu, *The Art of War* (quoted in Jackson 2014)

The U.S. Armed Forces may be the most capable military force the world has ever seen, yet this capability depends heavily on the use of technology. It is the integration of technology into all aspects of operations that has allowed the U.S. to gain and maintain a significant tactical advantage over our adversaries. However, to fill the gaps left vacant by its shrinking force while maintaining its current tactical advantage, our military must increase its dependencies on force multipliers like space-based capabilities. Thus, for example, as the Army continues to transition under the new Army Operating Concept (AOC) into a smaller and more capable force, force multipliers will be expected to contribute an even larger portion to the overall combat power. Unfortunately, this transition does not come without risk. As stated in U.S. Policy, in today's Operational Environment (OE) "potential adversaries are seeking to exploit perceived U.S. space vulnerabilities. As more nations and non-state actors develop counterspace capabilities over the next decade, threats to U.S. space systems and challenges to the stability and security of the space environment will increase" (Department of Defense [DOD] 2011a, 3). Clearly, our adversaries are developing capabilities that aim to reduce U.S. tactical advantages. To ensure this does not come to pass, the U.S. Armed Forces must follow the teachings of Sun Tzu and "prepare."

A. MOTIVATION

In modern warfare, the availability of space-based capabilities is often taken for granted. These capabilities are so thoroughly ingrained into operations that one can argue the U.S. Military has become too dependent on the tactical advantages these capabilities bring to the warfighter. Since the first significant use of space systems in support of combat operations during Desert Storm, the Department of Defense (DOD) has steadily increased its investment in space support capabilities. Looking back, it is evident that

> the Army has long recognized the positive value of space capabilities in enabling modern warfare. Satellite Communication (SATCOM) allows forces to operate over extended ranges; the Global Positioning System (GPS) delivers precise positioning, navigation, and timing; and space-based Intelligence, Surveillance, and Reconnaissance (ISR) systems provide unprecedented situational awareness of adversaries. (U.S. Army 2014a, 1–2)

But the Army is not alone in its leveraging of space-based capabilities, as the use of these capabilities has proliferated to such an extent that "military, civil, and commercial sectors of the U.S. are **increasingly dependent** on space capabilities, and this dependency is a **potential vulnerability as space becomes increasingly congested, contested, and competitive**" (Joint Chiefs of Staff 2013, I-2). Unfortunately, as the U.S. military transitions under guidance like the new AOC, this dependency is sure to grow, and adversaries will seek to take advantage of our dependency. In the OE of the future, the space and cyber-space domains will begin to take a dominant role in warfare, driving state and non-state actors to "invest in capabilities to protect their access and disrupt or deny access to others," and thus, it must be expected that "Army units will have to operate with degraded communications and reduced access to cyber and space capabilities" (U.S. Army 2014b, 11–12). Thus, the U.S. Military finds itself in a precarious position, stuck between opposing requirements of a shrinking force, operational readiness, and a threat.

These requirements force the U.S. military to shift combat power from local to external sources, which include space-based systems where, as indicated, known vulnerabilities exist. To say the U.S. military is prepared for the impacts of outsourcing combat power is optimistic. Most doctrinal sources point to the military being neither adequately trained nor equipped to effectively operate in a Denied, Degraded, and Disrupted Space Operating Environment (D3SOE) as outlined in the new AOC. The U.S. military has become dependent on the advantages that space brings the warfighter, yet it has done little to understand the potential risks of this dependency or to prepare for when we lose that advantage. The area of Operational Analysis (OA) is of most concern to this dissertation, specifically with regard to the inability of OA to provide operational and acquisitions decision makers with the information needed to make better decisions.

One area of OA where the U.S. military fails to adequately prepare for operations in a D3SOE is in operational planning. Today, commanders and staffs at all levels of the DOD have an unrealistic and sometimes non-existent expectation of the impacts to operations from a D3SOE. This is concerning because not only do we know that operations in a D3SOE is inevitable, but we have been told in National Policy to plan for it. As directed in the DOD Space Policy (2012), combatant commanders shall "develop and exercise operational concepts as well as tactics, techniques, and procedures to continue operations and achieve assigned national security objectives in an environment in which space capabilities have been degraded or denied" (11). Yet even with national directives demanding preparation, the author's operational experience show that most organizations routinely underestimate the threat from operations in a D3SOE. While some space planners are attempting to mitigate this threat, they often face significant obstacles from their own organizations, primarily due to the lack of any quantifiable source of information to justify their claims. Without such information, it is nearly impossible to successfully advocate for preparedness for operations in a D3SOE.

Another area of OA where the U.S. military fails to adequately prepare for operations in a D3SOE is in space Research and Development (R&D) and Acquisitions. Currently, as each service identifies emerging space capabilities, it allocates resources based on the potential utility they have in support of operations. There are two major issues with allocating resources in this way. First, it is done through only the most basic of heuristics, dependent on a qualitative assessment from various Subject Matter Experts (SMEs). Second, there is no common definition of what utility is or what it means to the warfighter. These issues significantly decrease a program's chance of success because there is neither a common nor a quantifiable metric to describe a system's contribution to the supported unit's overall operational effectiveness. How can we select the most feasible, mission-effective, and fiscally sound mix of alternatives if we have no means to quantify their contribution to operational effectiveness or to compare alternatives? As GEN Perkins said in his comments at the Naval Postgraduate School (NPS) on December 9, 2014, "In budget-constrained times it is important to have clarity of purpose" (Perkins

2014). To achieve this clarity, the U.S. military OA decisions of the future must be based on accurate and quantifiable information rooted in Measures of Effectiveness (MOE).

By using quantifiable metrics to screen out less operationally effective programs, resources can be better allocated to programs with the highest potential utility to the warfighter. While not all inclusive, the author believes that the U.S. military's failure during OA, specifically operational planning and acquisitions, is the primary contributor to the lack of preparedness for mitigating the effects of a D3SOE. This failure is likely due to the lack of two key capabilities:

1. A means to quantify the contributions of force multipliers like space-based systems and impacts from counter-space systems on operational effectiveness.

2. Operational and acquisitions decision support tools that can better articulate these impacts to leaders and decision makers as they plan for operations in a D3SOE.

By focusing on improving the OA process, supported by more accurate decision support tools, it is possible to provide military leaders with quantifiable information regarding force multipliers, and thus, should facilitate better decisions regarding preparation for operations in a D3SOE.

B. PROBLEM

Current OA methodologies lack decision support tools that can quantify the impacts from operations in a D3SOE. Thus, DOD space planners simply have no way to inform staff and leadership regarding the quantifiable impacts to friendly combat effectiveness from operations in a D3SOE. With over twelve years of experience as an Army space planner, it is the author's belief that this inability to inform the staff is largely due to the misconception among DOD planners that these effects are non-quantifiable or intangible, and thus outside or external to the scope of planning. While the utility of space systems is well understood, as well as the potential threats from adversary counter-space capabilities, neither can be easily measured, and thus, they are typically ignored during the Military Decision Making Process (MDMP) because they are considered non-quantifiable. Unfortunately, it is this perception of space-based

capabilities and other external force multipliers as non-quantifiable that is likely at the root of the problem. While ESINQ effects may be difficult to quantify, they are by no means non-quantifiable; up to this point, there has simply been no formal effort within the community to quantify them. This is not just an DOD problem either; the Modeling and Simulations (M&S) community as a whole typically either ignores the hard-to-quantify external dependencies and effects, aggregates them into the context, or implicitly models them in other modeled aspects. While models are by definition abstractions of reality, capturing “the essential aspects of a simuland to be represented in a model or simulation while excluding those aspects that are not relevant to the purpose of the model or simulation” (Modeling and Simulation Coordination Office 2017), to make the determination of relevance without any logical rigor is potential dangerous. As described by Johns Hopkins University Applied Physics Lab (JHU APL), “the simuland is often casually referred to as the ‘real world’ or as reality, actuality, or truth. However, no simuland actually achieves equivalence with the ‘real world’” (Johns Hopkins University Applied Phyisics Lab [JHU APL] 2017). In reality, simulations are an “abstraction drawn from the sum total of what is known, assumed, or projected about the simuland, called a ***referent***” (JHU APL 2017), which are often codified in terms of requirements and an operational concept. Model developers m understand the potential harm that can come from a model whose referent ignores potentially significant contributions to the outcome of the model. While fidelity addresses the accuracy of the model in representing the referent, how accurate can the model be if the referent is incomplete? Thus, while ignoring the irrelevant aspects of the real world is required in traditional Model Development Processes (MDP), in an era of unprecedented cross boundary and cross domain interoperability, the determination of where the line between relevant and irrelevant is drawn must be more carefully scrutinized. By moving away from considering external force multipliers like space-based effects as non-quantifiable, and rather describing such effects as External, Seemingly Intangible/Non-Quantifiable (ESINQ), a more accurate representation of these effects can be captured, one which addresses the possibility of quantifying the impacts of these ESINQ effects in the

referent, while highlighting the difficulty in doing so. For consistency in this document, the following four statements will be used to characterize an ESINQ effect.

- ESINQ effects impact the outcomes of the model.
- ESINQ effects are not modeled (external to the system/model boundary).
- ESINQ effects are difficult to quantify rather than non-quantifiable. If they are truly non-quantifiable they are not ESINQ.
- ESINQ effects are ignored without scientific rigor. If factors can be discarded following a logical assessment, they are not ESINQ; they have simply been determined to be insignificant for the purposes of the study.

It is the author's belief that the inability of current OA processes to account for ESINQ effects is due to the inability of traditional MDPs to recognize the existence of more than two contributors to a model's referent. Figure 1 provides the author's interpretation of the contributors to the referent of traditional MDPs.

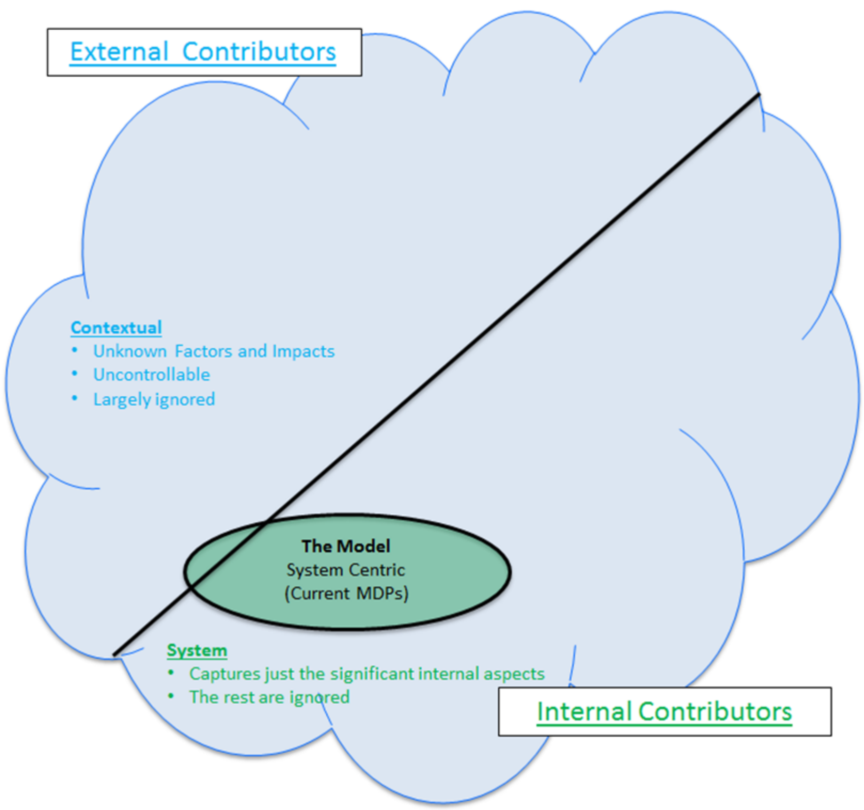


Figure 1. The Traditional MDP Referent

The blue cloud in Figure 1 represents a general view of the real world, which includes an infinite amount of modeling potential. In this example, the system is a generic model that, through abstraction, tries to capture some small piece of the overall environment. To do so, the model is developed using traditional MDPs, whose referent is primarily informed by just two contributing sources. The first source is internal contributors, which capture the key explicit system characteristics and effects that the modeler is interested in representing. The second source is external contributors, which bound unknown contextual effects of interest, typically seen as distractors, degraders, or noise. The intent of the model (the green oval) is to capture enough key aspects of the system in the context of the physical world to provide an approximation of the system of interest, which includes some of the interactions with the environment. Because of this focus, the majority of the model's inputs are based solely on the system of interest, specifically the quantifiable details derived internal to the system, with only minimal accounting of the referent of other contextual factors. Unfortunately, in the OE of today where modern systems tend to rely heavily on the contributions from external force multipliers—like space-based systems—for the generation of internal combat power, this approach can potentially ignore a sizeable portion of significant input factors during the establishment of the referent. These sources, like external dependencies and ESINQ factors and effects, often reside in the area of the OE (the blue cloud) that is typically ignored during the development of the referent used in traditional MDPs. In order to account for these contributions, which are often very subjective and difficult to quantify, traditional MDPs must acknowledge that not only do additional referent contributors exist, but also that they can be significant. By breaking away from the inflexible, closed system approach of traditional MDPs, it should be possible to capture a more accurate representation of the OE in the referent, as seen in Figure 2.

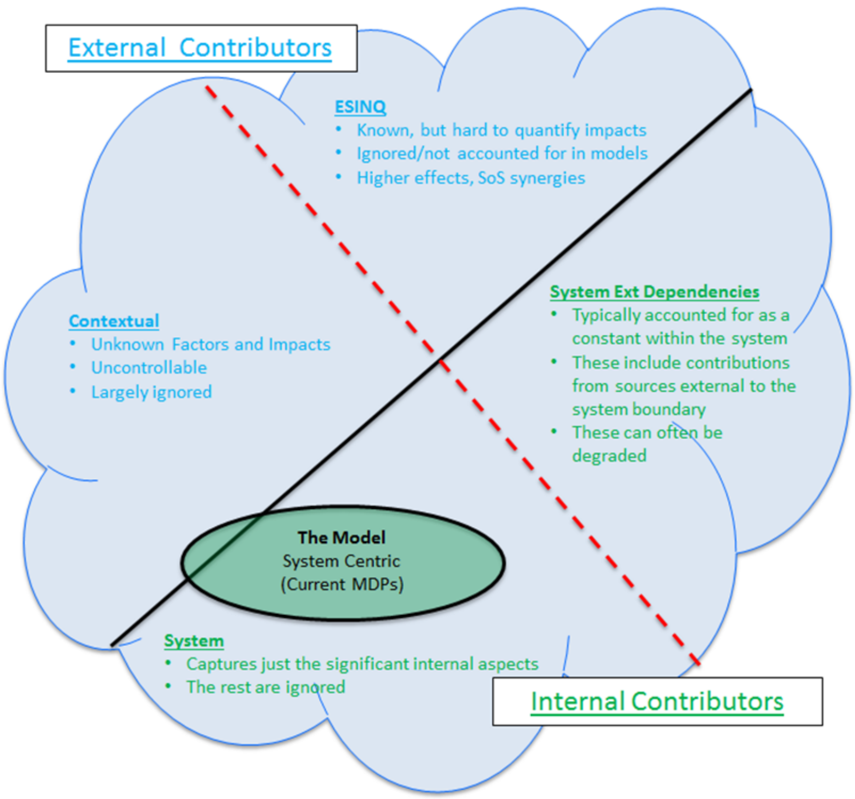


Figure 2. The Expanded MDP Referent

By acknowledging that a more refined referent can be achieved by sub-categorizing the contributions of both internal and external contributions, it will be possible to form a more holistic understanding of the OE, the portion of the real world of interest that defines the context for the referent used during the MDP. This improved understanding can first be achieved by delineating between the different sources of internal contributions to the referent. By separating a model's input sources into two areas—a system's internal contributions and a system's internal contributions that are externally dependent—it is now possible to decouple any dependencies the system has on external resources. Unfortunately, due to the focus on explicit modeling techniques, most traditional MDPs either ignore these external dependencies or aggregate them with internal contributions during the establishment of the referent. Thus, the two internal sources cannot be observed independently, resulting in the inability of most MDPs to account for the impacts that external dependencies have on internal metrics of operational effectiveness. Once separated, users can degrade the portion of the system's contributions

that is dependent on external support, which facilitates the quantification of the operational impacts due to a D3SOE, a key outcome of this work.

Next, this understanding can be further improved by delineating between the different sources of external contributions to the referent. By separating the external contributors to models into two areas, contextual contributions and ESINQ contributors, it is possible to highlight a fourth area of potential contributions to the referent that is currently unaccounted for within traditional MDPs. The key difference between the two is that contextual factors are by definition unknown and/or uncontrollable, but ESINQ factors are not; they are both known and controllable, though they are often extremely difficult to quantify. By recognizing ESINQ factors and effects as potentially significant model contributors, and acknowledging them as known, albeit difficult to quantify, the inclusion of ESINQ systems like space-based systems into the referent is facilitated. This more inclusive process supports the quantification of the operational impacts from these systems, which is another key outcome of this work. While this improved understanding of the OE does not change the fact that traditional MDPs fail to adequately account for either external dependencies or ESINQ factors and effects in the referent, as seen by the lack of overlap of the model with the four potential contribution sources in Figure 2, it does set the conditions for a more inclusive MDP capable of accounting for them.

C. RESEARCH QUESTIONS

The primary question driving this research is as follows: Can current MDPs be modified to account for ESINQ effects within models? If so, can these ESINQ-enabled models be used to quantify the operational impacts from ESINQ effects? With these questions in mind, the aim of this work is to identify how M&S and Model Based Systems Engineering (MBSE) can be used to address observed gaps within operational and acquisitions planning by supporting better decision making through the quantification of ESINQ effects. By providing better information to decision makers, information that is capable of capturing a more accurate understanding of the OE, a more robust solution set should be possible. In constructing this question, the following supporting questions were also identified for their potential in supporting OA decisions:

1. What models are capable of representing the contributions from external dependencies and ESINQ effects, and to what level of resolution?
2. How can MBSE and M&S be used to aid decision makers within the OA fields to filter, design, configure, compare, select, and allocate resources to emerging capabilities?
3. Can an emerging system's physical and operational models be linked through design responses? Can this interaction be captured in a meta-model that is tied to metrics of operational effectiveness?
4. Can ESINQ meta-models be used to improve current operational and acquisitions decision support tools to provide a more robust solution with regard to operational effectiveness?

In addressing the primary and supporting research questions, this dissertation fills some significant gaps in the ability of current MDPs to capture ESINQ effects. By providing a methodology that can bound ESINQ effects within a model, a better representation of the OE in the referent will be possible. This more complete understanding of the OE will improve the models developed through current MDPs; will improve the assessments generated from MBSE analysis methodologies; and support more informed decisions regarding both the use and allocation of resources. Together, these improvements will better address the gaps described in the motivation and problem sections, and support U.S. military space professionals to make more accurate and informed decisions as we "prepare" for operations in a D3SOE.

D. PRIMARY AND SECONDARY CONTRIBUTIONS

To address the inability of traditional MDPs to account for the contributions from external dependencies and ESINQ effects, an improved MDP is needed that can enable the inclusion of all four of the referent contributors. This work expands the M&S body of knowledge through the development of a formalized methodology to account for, or bound, ESINQ factors and effects within the MDP. The intent is to address the lack of synergy in traditional MDPs by developing an Implicit Model Development Process (IMDP) as well as a set of operational and acquisitions decision support tools to support the quantification of impacts from ESINQ effects within a model. This expansion

improves the utility of current decision support tools, and results in a better understanding of the impacts of ESINQ effects on metrics of operational effectiveness.

1. Primary Contribution

This work demonstrates how the IMDP can be applied to improve model definition and development, the two primary steps of most traditional MDPs (the third step is model analysis). This improvement enables users to gain novel insight into the workings of the model and account for the external dependencies and ESINQ factors and effects that currently go unaddressed in traditional MDPs, and while not discussed in detail here, a more in-depth discussion of the strengths and weaknesses of traditional MDPs is found in Chapter II. Because traditional MDPs tend to underwhelm the model definition step, devoting a relatively small portion of the overall resource budget to what most systems engineers would consider the critical step, the models produced based on this definition are often more inaccurate then they could be. This problem is further complicated by the fact that most traditional MDPs take a purely explicit model development approach, directing users to avoid hard-to-quantify input sources for fear of injecting subjectivity into the study. Thus, most traditional MDPs are ill-equipped to model systems or effects that can be considered ESINQ. The IMDP complements traditional MDPs by formalizing a methodology for expanding the model definition step to account for ESINQ effects of interest in the referent. While the IMDP can serve as a standalone MDP, it was developed to augment traditional MDPs in order to improve the ability of the model to capture the actual OE. Specifically, the IMDP focuses on including the impacts from external dependencies and ESINQ factors and effects. Through the use of the IMDP, a more accurate representation of the OE can be implemented in the model, greatly improving the model's fidelity and ability to link a system's characteristics, to include inputs from external dependencies and ESINQ effects, to metrics of operational effectiveness. To demonstrate, Figure 3 gives a general description of how the IMDP can be applied to a generic MDP to produce an ESINQ-enabled model, capable of quantifying the impacts of ESINQ systems and effects on operational effectiveness.

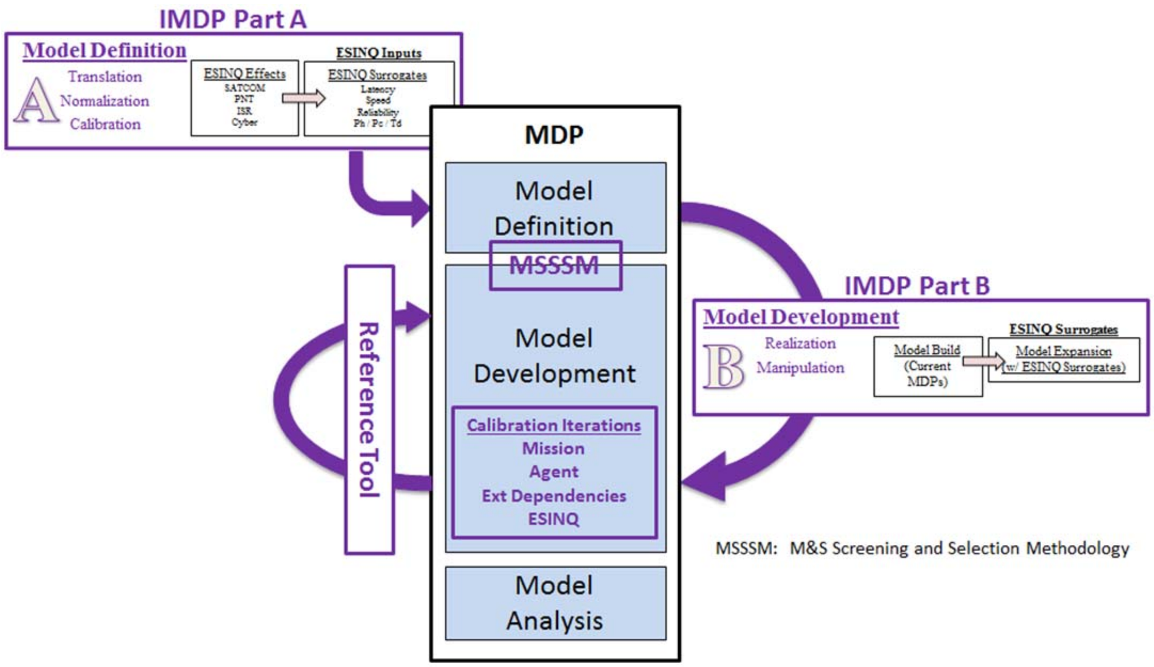


Figure 3. Implicit Model Development Process

Differing from traditional MDPs, part A of the IMDP puts a significant amount of emphasis into the definition of the model. In this step, ESINQ factors and effects of interest are identified, translated, normalized, and then calibrated in preparation for their inclusion within the model through an implicit modeling technique that utilizes surrogate factors. In part B, the surrogate factors can be instantiated within the model and then manipulated to generate a range of responses that can be used to bound the impacts of these ESINQ effects on measures of operational effectiveness. It is the bounding of these responses that is of interest to this work because it facilitates the development of meta-models capable of representing the impacts of ESINQ effects of interest on measures of operational effectiveness. These meta-models can in turn be used to improve the accuracy of operational and acquisitions support tools, giving planners the means to provide decision makers with the quantifiable data necessary to make better decisions. Additionally, because the IMDP enforces traceability to a reference tool throughout the process, partial validation of the ESINQ-enabled model is achieved. Through the use of the IMDP, a more inclusive model can be developed, one capable of accounting for a larger portion of the OE in the referent, as seen in Figure 4.

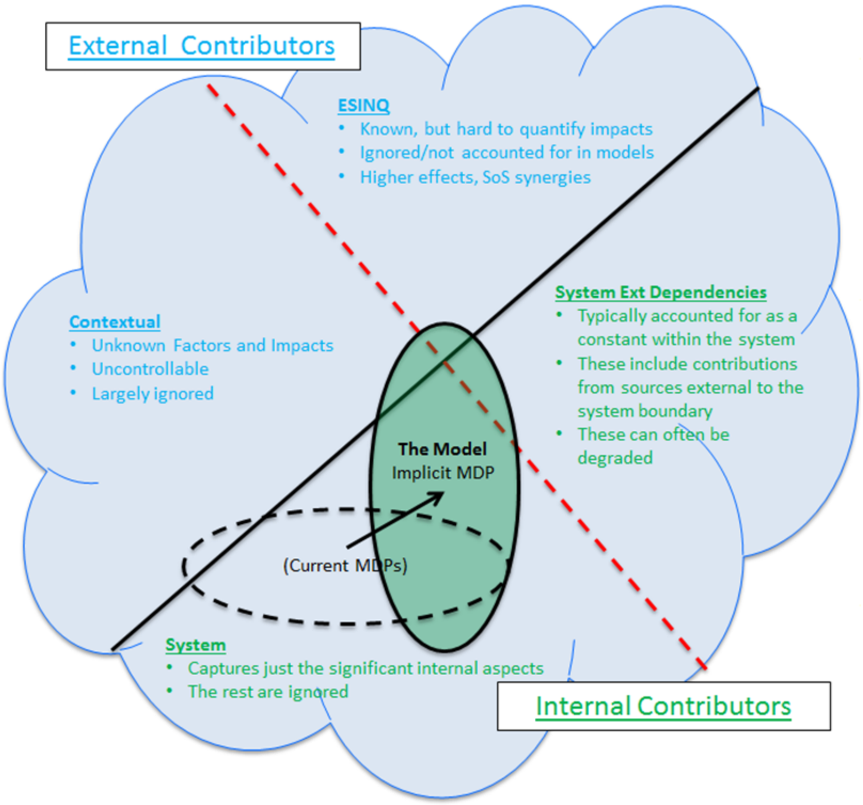


Figure 4. The IMDP Referent

Through the use of the IMDP, the model (green oval) can capture a larger portion of the OE through the use of pre-existing surrogate factors within the model to represent the ESINQ effects and external dependencies of interest. This ESINQ-enabled model has two significant contributions. First, it allows us to quantify through meta-models the operational impacts due to ESINQ factors and effects, which can be used to support operational support tool development. This work puts a more formal effort into the utilization of the operational model meta-models for use within external tools, specifically in the development of operational decision support tools. Second, when used in conjunction with a synthesis model of a system's physical components, a more thorough Trade Space Exploration (TSE) can be conducted during design because the underlying operational model can more accurately represent the OE. This is critical for acquisitions professionals executing analysis of emerging systems whose operational impacts often reside in areas considered as ESINQ, like space-based systems. Through

this use of the IMDP, it becomes possible to conduct quantifiable system analysis capable of assessing the contributions of ESINQ factors and effects (like space-based capabilities) to friendly combat power; the impacts to operational effectiveness from adversary use of ESINQ factors and effects (think counter-space activities); and the capabilities of non-traditional/ESINQ-enabled systems (emerging space systems) to mitigate adversary threats. This capacity will greatly improve the OA activities of the United States, as well as improve the quality of the decisions resulting from the analysis.

2. Secondary Contributions

This dissertation aims to expand the overall capability of current MDPs and to improve the accuracy of models through a formalized IMDP that can account for ESINQ factors and effects. In accomplishing this, five secondary contributions are made that address many of the problems described earlier in this chapter. These included the development of an ESINQ-enabled combat model, an operational support tool, an acquisitions support and TSE tool, the development of an M&S Selection and Screening Methodology (MSSSM), and the expansion of M&S and MBSE processes. A depiction of the IMDP primary and secondary contributions can be seen in Figure 5.

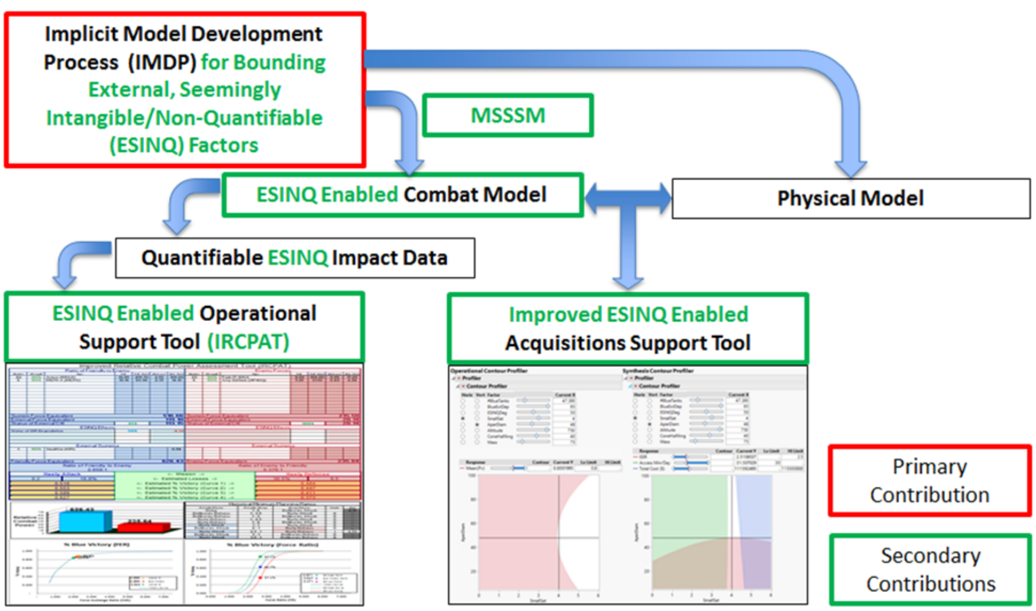


Figure 5. IMDP Primary and Secondary Contributions

The primary contribution of this work is generalized, and supports the expansion of the referent of traditional MDPs to account for ESINQ factors and effects. The secondary contributions on the other hand are more specific, and focus on the motivation for this work, which is the quantification of the impacts from space-based capabilities and operations in a D3SOE on operational effectiveness. A brief description of each of these secondary contributions is provided, and will be discussed in more detail throughout this dissertation.

a. ESINQ-Enabled Operational (Combat) Models

Space planners do not currently have access to an operational model that can fully demonstrate the impacts of a D3SOE on operational effectiveness of the operational force. Without a quantifiable and consistent means to evaluate a system's impact on higher level MOEs it is not possible to compare mitigation strategies, and decisions made in this manner will produce outcomes that have little traceability to actual MOEs. The most significant outcome from the IMDP developed in this dissertation is in the creation of ESINQ-enabled entity models that more accurately represent modern operations as outlined in the new AOC, to include dependencies on space-based capabilities and the impacts from counter-space capabilities. Because entity level models (physics based) are uncommon at the tactical level, the outcomes of this work will support the translation of ESINQ effects to improve the aggregate models and tools commonly used at the tactical level. This will provide a much needed tool for planners to integrate D3SOE activities, allowing them to quantify operational impacts from a D3SOE and better support the U.S. military as it "prepares" for an uncertain future. The ESINQ-enabled operational models will be discussed further in Chapter IV.

b. ESINQ-Enabled Operational Support Tool

The tool that is most widely used to support Army operational planning is the Force Ratio Calculator (FRC), an Excel based model that estimates the Relative Combat Power (RCP) of two opposing forces based on mission set and force size. Unfortunately, "force ratios do not include the environmental and human factors of warfare" (Department of the Army [DOA] 2005, 3–31), nor do they account for external

dependencies or contributions from sources of combat power outside of the system boundary. Thus, Army Course of Action (COA) development cannot accurately capture the RCP of the opposing forces, forcing leaders to make decisions with an incomplete and inaccurate assessment of the OE, which can have unforeseen costs in lives, time, and money. Therefore, the FRC tends to underestimate the capabilities and vulnerabilities of the forces being modeled and as noted by Zanella in his thesis (2012), produces RCP ratios where “the estimated ratios are probably too low” (8). Using the ESINQ-enabled model and the output from a large scale Design of Experiments (DOE), this dissertation developed an improved version of the FRC that provides planners the means to quantify the impacts from ESINQ factors and effects. By highlighting space dependencies and threats that were ignored in the past, a more accurate assessment of RCP can be achieved. The ESINQ-enabled operational support tool will be discussed further in Chapter V.

c. ESINQ-Enabled Acquisition Decision Support Tool

This dissertation developed an ESINQ-enabled acquisition decision support tool for use by space R&D and Acquisitions communities to conduct TSE. This tool allows decision makers to visualize and explore the design trade space of emerging space systems earlier in the design life cycle, and gain a better understanding of the systems and their interactions within a more accurate representation of the OE prior to resource allocation. By linking operational and physical design feasibilities to a quantifiable assessment of a system’s impacts to operational effectiveness, imbedded in an ESINQ-enabled representation of the OE, decision makers can make better informed decisions regarding the resource allocation of competing capabilities. The ESINQ-enabled acquisition decision support tool is discussed further in Chapter V.

d. M&S Screening and Selection Methodology

In most MDPs and analysis methodologies, users are assumed to use an appropriate M&S package for the purpose of the study and the analysis they are interested in conducting. Thus, no formalized techniques have been defined to support M&S screening and selection. Unfortunately, there are two major issues with this assumption. First, most users do not understand the breadth or depth of available M&S

resources. Second, most users typically select the M&S package they are most accustomed to, without consideration for the utility of that package for the specific problem. This is a significant disadvantage of current MDPs, and results in the majority of analysts selecting non-optimal M&S packages. This dissertation will develop a formalized MSSSM that will support a better investigation of potential M&S packages, and by doing so, increase the likelihood of selecting a more appropriate M&S package for use. The MSSSM will be discussed in Chapter III.

e. Expanding the Acceptability of M&S and MBSE

MBSE is an emerging branch of Systems Engineering (SE) which emphasizes the importance of modeling through the formalized application of M&S throughout the SE process. It is a capability-based decision making process which ties OA decisions to quantifiable impacts on metrics of operational effectiveness, and thus allows for better decisions regarding the selection of alternative designs. This work expands the understanding, use, and the acceptability of M&S and MBSE by improving current MDPs through the execution of the IMDP, as well as applying it for the first time to the space systems operational and acquisition fields. The expansion of the acceptability and use of M&S and MBSE is discussed throughout this dissertation.

E. METHODOLOGY

For this dissertation, the author used quantifiable and sequential mixed methods research using MDPs, MBSE, and effects-based decision making. By synergistically applying these processes and methodologies to a common problem, it will be possible to better align early conceptual design modeling to metrics of operational effectiveness. Thus, through the development of a IMDP and a set of improved operational and acquisition support tools, this work enables better informed decision making by providing leaders with more robust information regarding the impacts of ESINQ factors and effects (space systems) on operational effectiveness of the warfighter in a D3SOE.

1. Modeling Outline

In achieving the outcomes described in this chapter, three models were developed to generate the required data and tools. These models included an operational model, a physics based model that captures the operational requirements and constraints of systems and their impacts to operational effectiveness; a synthesis (physical system design) model, to capture the physical requirements and constraints of emerging space systems; and a linked model, where meta-models of both the operational and synthesis models are linked via common response factors for use in decision support tools. This modeling outline can be seen in Figure 6.

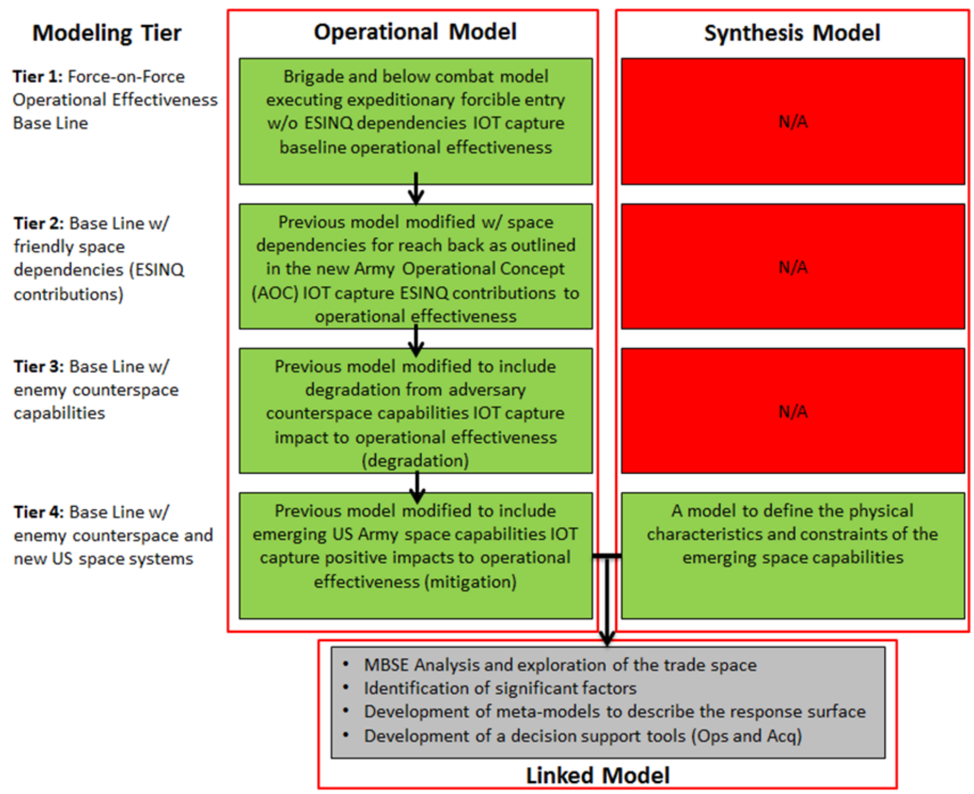


Figure 6. Modeling Outline

The left side of the figure shows the four tiers of operational model development, the right side shows the synthesis modeling, and on the bottom we see the linked model. The primary contribution of this work was accomplished in Tier 2, where the IMDP

supports the development of a physics based operational entity model that can account for ESINQ factors and effects through the use of surrogate factors and then quantify the impacts of these effects on operational effectiveness. This contribution supports the development of all but one of the secondary contributions listed in this work, including the development of an operational decision support tool, an aggregate model that is improved through the application of ESINQ-enabled meta-models. The remaining tiers, the synthesis model and the linked model are used to support the development of the acquisitions decision support tool.

The operational model will be developed incrementally in four tiers. In Tier 1, a model will be created that captures the best possible representation of the scenario within the OE as possible, without consideration for ESINQ factors or effects. In Tier 2, the model will be expanded to include the ESINQ factors of interest, which in this work captures space support requirements like dependencies on GPS, SATCOM, and ISR. In Tier 3, this model will be expanded again to include adversary counter-space capabilities. Finally, in Tier 4, the model will be expanded to include emerging space capabilities like Small Satellites (SmallSats) and High Altitude Atmospheric Satellites (HAAS) in order to capture their ability to mitigate the effects of adversary counter-space capabilities. This model, executed in conjunction with a DOE, will produce the data needed to create a meta-model that can be used as a surrogate in other models and tools.

The synthesis model developed in Tier 4 is actually the most complex of the models developed in this work. Because physical characteristics impact Measures of Performance (MOP), and user inputs, requirements, and constraints impact system characteristics, the development of a model that can produce a representation of the trade space of emerging systems while maintaining the flexibility to allow user input is extremely complicated. To reduce the complexity of this process, this work expands upon the thesis work of Ordonez (2016), and use a modified version of his SmallSat synthesis model for use in this work. Like the operational model, this will be used in conjunction with a DOE to produce a good fitting meta-model that represents the user settings in the synthesis model with the expected impacts on metrics of operational effectiveness.

The linked model, while simply the combination of model representations, or meta-models of the operational and synthesis models, will be the final model developed in this work. The purpose of this model is to provide the framework for the development of a visual decision support tool that will allow users to explore the system design trade space of system alternatives. This tool will highlight how user requirements, constraints, and decisions affect a system's impact to operational effectiveness. Unlike other methods of evaluating alternative systems, this tool will allow for a complete and thorough investigation of system tradeoffs that can simultaneously screen alternative designs for both operational and physical design feasibility.

2. Research Scope

National Policy and Doctrine establishes the need for capabilities, methodologies, and Tactics, Techniques and Procedures (TTP) to prepare for and mitigate the operational impacts of adversary counter-space activities. This research focuses on developing an IMDP and a set of operational and acquisitions decision support tools that will support U.S. military operations and acquisitions decision makers to make better decisions. By providing quantifiable data that links metrics of operational effectiveness to physical design parameters, decisions regarding the resource allocation of emerging space systems should be improved. Yet this is a difficult problem, and rather than attempting to accomplish such a complex undertaking, this research was scoped in the following ways to reduce the overall complexity of the problem.

First, this work serves as a proof of concept, and establishes a methodology for accounting for ESINQ factors and effects within the MDP. By avoiding the highly detailed, high resolution, and Verification, Validation, and Accreditation (VV&A) M&S packages typically used within the DOD, the complexity of model development was significantly reduced. This allowed the research to investigate a broader range of research questions, significantly increasing the contribution of this work to the overall body of knowledge. Additionally, to further reduce the complexity of this investigation, the scope of this work focuses on the tactical level, specifically the Brigade and below. Thus, the models developed in this work were relatively small, ranging in size from 30 to a few hundred

agents, and used relatively short conflicts, ranging from minutes to hours. While the direct results of this work may not be adequate for long term use by the U.S. military, it can be used to fill known capability gaps by providing products that have immediate applicability to current operations.

Next, because one of the secondary contributions of this work was the development of an acquisitions decision support tool to help visualize the design trade space prior to resource allocation, this work focused on the conceptual design phase of the SE process. Thus, the majority of the synthesis modeling done in this work was intentionally low resolution. In order to maintain the flexibility of the tool to allow users to fully explore the design trade space, it must be capable of accepting a wide range of user inputs, to include requirements, constraints, thresholds, and goals. By developing a low resolution synthesis model which captures only the dependencies and interactions of the major design factors, a more robust model for use in early TSE was produced.

Lastly, because another of the secondary contributions of this research was the development of an operational decision support tool that could provide utility to operational space planners, this work focused on solutions that were easy to use, could be rapidly developed (minutes not hours), were free and openly available at the unclassified level, stochastic, and constructive in nature. These choices were made by the author in order to maximize the extent to which the products developed in his work could support operational space planners, specifically focusing on mission planning, training, and exercises, where the most impact can be made in preparing for operations in a D3SOE.

F. ORGANIZATION

This dissertation is organized into six chapters. Chapter II reviews the prior work and literature regarding this research, focusing on the current threat, mitigation strategies, the Army's use of space, the MDMP, and gap analysis. Chapter III outlines the primary contribution of this dissertation through a detailed presentation of the IMDP. Chapter IV includes a complete demonstration of the IMDP for a space specific problem. In this chapter, a full implementation of the IMDP is conducted, taking the reader through the modeling phase, and then through the analysis phase to produce a set of linked meta-

models capable of describing the impacts of ESINQ factors and effects on operational effectiveness. Chapter V discusses the application of the meta-models developed in Chapter IV to improve operational and acquisitions support tools. The development of these tools will be discussed, and their applicability to support operation planning, TSE and analysis, and to support acquisitions decision making will be demonstrated. Chapter VI summarizes the dissertation's key contributions and recommends future improvements to the methodology and tools described in this dissertation. Appendix A provides the MSSSM, which was executed to justify the selection of the M&S package used in this work. Appendix B supplements Chapter II by providing a more in-depth discussion regarding space threats and dependencies. Additionally, a Supplemental section is provided which gives a brief description of the two Microsoft Excel tools produce in this work, the IMDP and the IRCPAT, as well as how they can be requested.

II. A FOUNDATION

> If you know neither the enemy nor yourself, you will succumb in every battle.
>
> —Sun Tzu, *The Art of War* (quoted in McNeilly 2017)

The purpose of this chapter is to provide more background regarding the motivation of this dissertation, focusing on the problem that it seeks to address and the context in which that problem resides. Specifically, this chapter will be broken into three sections, a foundational section, a framework section, and a keystone section. The foundation section, “The Three Knows,” will address U.S. space dependencies, adversary threats and capabilities, how the Army currently conducts operations and planning, as well as the expected operational impacts to U.S. operations from these threats. This section will frame the context in which the problem exists and provide Army specific motivations for this work. The framework section, “Mitigation Strategies and Gaps,” will discuss current and emerging Army mitigation strategies, focusing on doctrine, technologies, and Army modeling. This section will provide more general details regarding the linkages between the observed problem and the perceived organizational gaps, and while still addressing Army operations, will begin to highlight the more generic underlying issues within M&S practices. The keystone section, “M&S Community Modeling Gaps,” will close out the chapter with a discussion on what the author believes to be the underlying M&S gaps that have to this point contributed to the failure of the United States to adequately address adversary use of counter-space systems in both operational planning and acquisitions. This section will provide a more general discussion of the modeling gaps, and while decoupled from Army specific issues, as the keystone section, will tie the observed problems to gaps within the M&S community, highlighting potential areas for improvement. By organizing this chapter in this manner and exploring the problem and gaining an understanding of its context through the foundation, framework, and keystone sections, a conceptual bridge can be built to take us from the observed problem to a potential solution.

A. FOUNDATION: THE THREE KNOWS

The U.S. military continues to place a greater emphasis on the importance of space as well as the advantages that space brings the warfighter. Over the past 10 years, the increasing emphasis on the positive value of space capabilities has been reflected in the growing occurrences of space verbiage in National Policy and Doctrine; where space support and capabilities have moved from brief acknowledgments of just a few sentences in the early 2000s, to the forefront of policy and doctrine in recent documents. Throughout these documents, the "Army has recognized its critical dependence on space capabilities across the whole force" (U.S. Army 2014a, 2). While the doctrine emphasizes the potential vulnerabilities of this critical dependency, it does not address any solutions, nor does it attempt to look at this vulnerability through the lens of the expected OE of the future, specifically operations in a D3SOE. This is a key point of this work; if the U.S. military does not consider this threat in the new and expected OE, we will produce mitigation strategies and systems that were designed for a different problem. This is a type I error and all too common in the DOD acquisitions community.

This section is organized into three sub-sections, according to what Lung (2011) defines in his work as the "three Knows: Know yourself, know your enemy, and know the environment" (Ch. 1). The "Three Knows" parallels the quote from Sun Tzu that introduced the chapter and emphasizes the importance of understanding your own capabilities and limitations, as well as those of the adversary. This section will describe U.S. space dependencies, the major adversaries and their counter-space capabilities, as well as the environment in order to provide a better understanding of the problem. By understanding these aspects of the problem, as well as the overall OE in which it resides, decision makers can make more informed decisions when addressing threats and potential mitigation strategies when considering operations in a D3SOE.

1. Know Yourself

In the new AOC (2014b), the Army considers space-based capabilities as "first order capabilities the Army must possess to win in a complex world" (31). The term "must" is a fairly definitive statement. Couple this with other Army statements like the

Army must "assure uninterrupted access to critical communications and information links (satellite communications; position, navigation and timing; and intelligence, surveillance, and reconnaissance) when operating in a contested, congested, and competitive environment" (U.S. Army 2014b, 32), and we are quickly faced with a difficult problem. Simply put, in order for the Army to win in a complex world, it must have and maintain its access to space-based capabilities. Yet to do this effectively the Army must first embrace the idea of "knowing itself," and strive to fully understand how it operates, the resources it uses, how it uses them, and all the intricacies that go with it.

a. U.S. Space Dependencies

The U.S. military achieves overmatch through a balanced combination of technology and force structure. In some cases, U.S. forces are actually much smaller than adversary forces, and sometimes even less capable when evaluated with traditional combat effectiveness metrics, yet through the expert application of technology in support of operations, the U.S. military is able to achieve overmatch. It is the application of technology that the United States arguably does better than any other country in the world, which allows the U.S. military to achieve operational superiority. But this comes with a cost, and to maintain overmatch it requires a substantial amount of space support. In fact, "the U.S. Army is one of the largest users of space-based capabilities within the DOD" (DOA 2009, 6), and likely one of the largest consumer in the world. This dependency on space support is at the crux of the problem, and "although our advanced space and cyber-space assets give us unparalleled advantages on the traditional battlefield, they also entail vulnerabilities" (DOD 2008b, 22). In order for the U.S. military to "Know Itself," it must understanding these dependencies and vulnerabilities.

According to the Union of Concerned Scientists (UCS) the United States is the largest operator of space systems in the world. As of August 2015, there were 1305 operational satellites on orbit, of which the United States accounts for over 42%. While China and Russia, the next two biggest satellite operators are heavily invested in space as well, they only account for 11% and 10%, respectively. Of the 549 operational satellites currently operated by the United States, over half of them could be shown to have direct

operational relevance to military operations, and this does not even include the host of commercial satellites the U.S. currently uses. Thus, it is easy to see why many countries are confident in the assertion that the U.S. military is dependent on space-based systems. Using the satellite database compiled by the UCS (Union of Concerned Scientists 2015), the overall breakdown of U.S. military/government satellites (a sub-set of the 549 operational satellites), to include commercial satellites, can be seen in Figure 7.

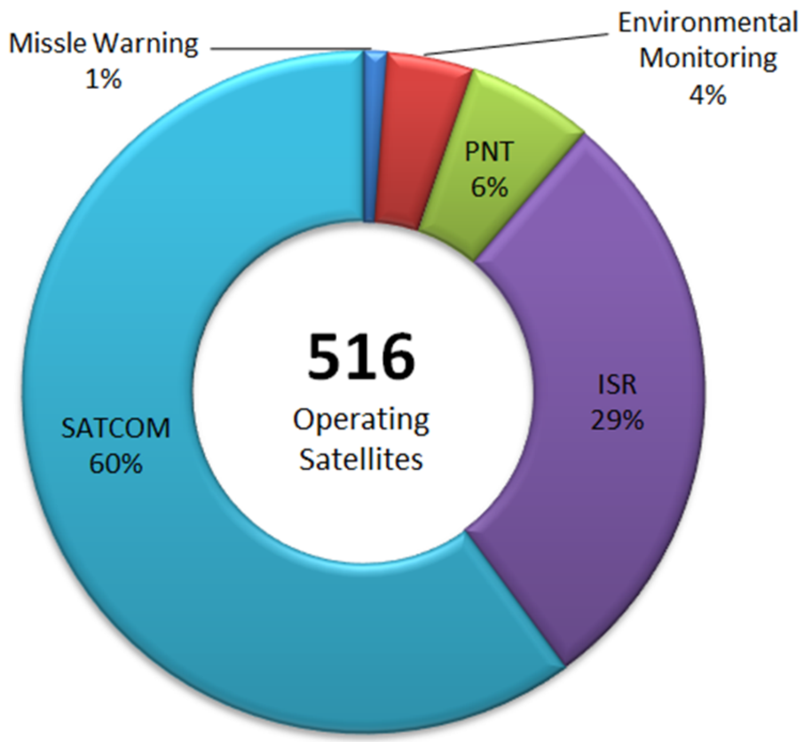


Figure 7. U.S. Space Dependencies by Mission Area

SATCOM accounts for the majority of military use of U.S. space systems, with 60% of all satellites being focused on communications. The ability to rapidly disseminate information, SA, and execute Battle Management, Command and Control (BMC2), gives the U.S. military an unparalleled ability to quickly execute the decision making cycle—a significant advantage over adversaries who require more time to gather, process, and disseminate the information needed to make decisions. ISR is the second most prominent use of space systems by the United States, accounting for roughly 30% of all U.S. space systems. The ability to maintain up to date Situational Awareness (SA) regarding

adversary force distribution, disposition, strength, and location is often critical to decision making, and "supports the development of intelligence that supports mission success, and other actions that may influence the commander's current and future operational decisions" (DOA 2014, 3–27). PNT accounts for another 5%, and while comparatively small when compared to SATCOM and ISR, due to its integration into the civilian sector has made it arguably the most critical. GPS allows decision makers to more accurately assess operations, the threat, and the environment, and allows them to make quicker and better informed decisions, which can drastically increase the operational tempo of the U.S. military. Together these three mission areas account for roughly 95% of all military satellite missions. Since operational requirements typically drive development, it does not take a huge leap of logic for our adversaries to surmise that U.S. dependency on space systems likely follows this same breakdown. The depth of space integration into operations highlights a potential dependency that is echoed in the Army Strategic Planning Guidance, which states that "the Army's warfighting functions, weapons and battle systems are vitally dependent on space capabilities to achieve land dominance" (U.S. Army 2013a, 6). Thus, while the level of dependency on space is debatable, it is easy to see why adversary nations focus counter-space development in these areas.

b. MDMP: How the Army Plans

The Army has a clear and concise MDMP that has been refined over the course of many decades, producing a detailed "planning model that establishes procedures for analyzing a mission, developing, analyzing, and comparing courses of action against criteria of success and each other, selecting the optimum course of action, and producing a plan or order" (DOA 2005, 3–1). Army planners are extremely skilled at the execution of this process, and because of this skill, often take the lead in joint planning environments. While the MDMP is heavily used by the Army, it does have its limitations. First, it is resource consuming, both in time and in manpower, and therefore it is seldom used below the battalion level or in environments where the OE changes rapidly. Second, and more to the point of this research, it is only as good as the information that is provided. Figure 8 shows a graphical depiction of the MDMP.

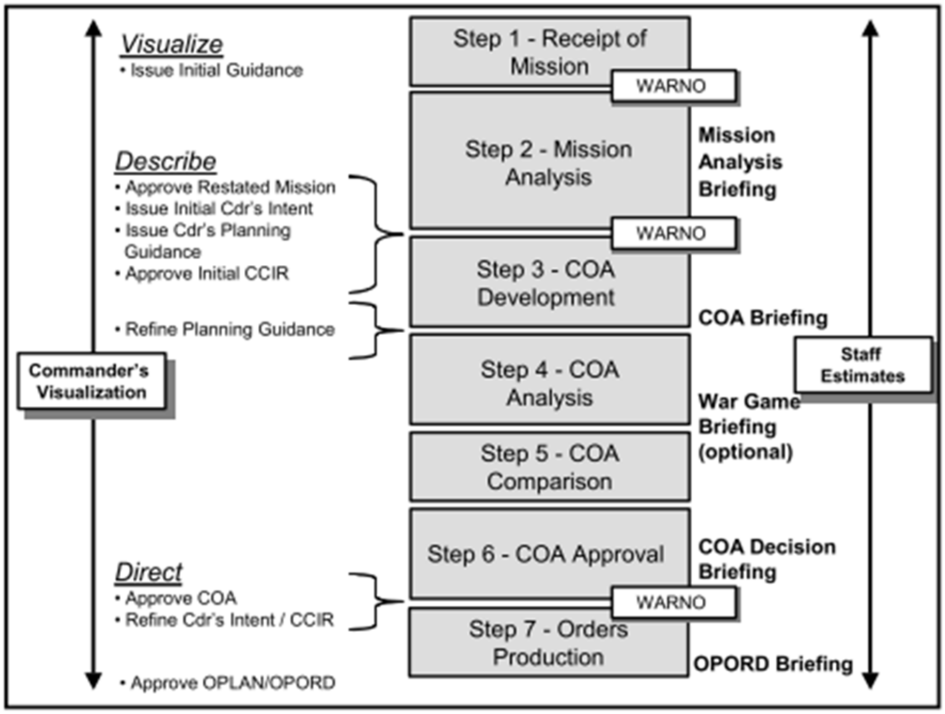
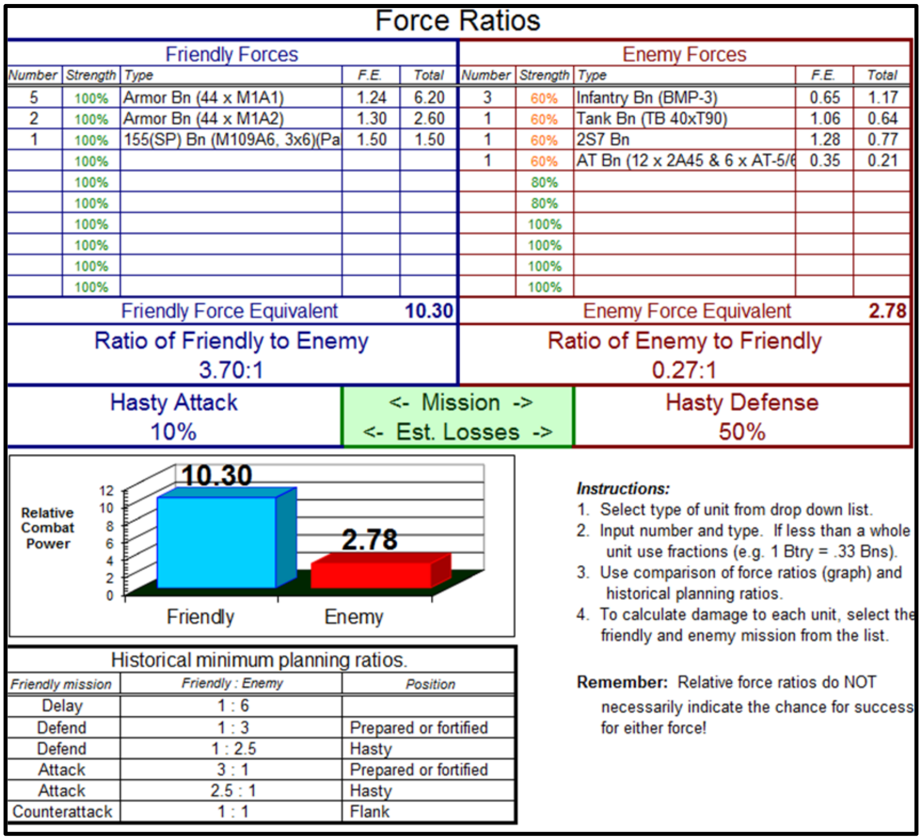


Figure 8. The Role of the Commander and Staff in the MDMP.
Source: DOA (2005, Fig. 3–1).

The MDMP is a seven-step process that takes planners from receipt of the mission through orders production. The step that is of most concern to this work is step three, COA Development. During this step, opposing forces are analyzed and multiple COAs are developed that allow friendly forces "to generate overwhelming combat power at the decisive point to accomplish the mission at least cost" (DOA 2005, 3–115). A Commander will evaluate the staff's proposed COAs, and using his unique understanding of the OE, make a decision based on his/her acceptable level of risk and the mission objectives. During the first phase of this step, adversary forces are weighed against friendly forces, then threats and vulnerabilities are assessed, and finally combat powers are compared. This progression is often referred to as RCP analysis, and is defined as "the total means of destructive and/or disruptive force that a military unit/formation can apply against the opponent at a given time" (DOA 2005, 3–115). The tool that the Army routinely uses to conduct RCP analysis at the tactical level is the FRC, which can be seen in Figure 9.



RCP is a ratio of the Blue combat power over the red, and the higher the better. Leaders use this information to make decisions regarding force allocation. In this example, Blue is executing a hasty attack versus a hasty defense, where a RCP of at least 2.5:1 is recommended. Based on the assessed force strengths, blue has a RCP of 3.70:1, and thus, a decent advantage.

Figure 9. Force Ratio Calculator. Source: Craig (1999).

The tool was originally designed in 1999 by MAJ J. Craig during his CGSC course work, and allows planners to assess the RCP by selecting the type, quantity, and strength of the opposing forces, then selecting the missions of each. In this example, the friendly force has a 10.30 to 2.78 (3.7 to 1) RCP advantage, which is typically considered more than acceptable for an attack against a hastily prepared defense, which historically calls for at least a 2.5:1 advantage. While the FRC is a simple tool, which aggregates combat into the most simplistic of quantifiable measures, specifically system versus system without any accounting for additional sources of combat power, it is still the primary operational planning tool for accessing RCP of opposing forces.

2. Know Your Enemy

While the first part of this section introduced U.S. dependencies on space, this second part will introduce the reader to the adversaries and the threat posed by their counter-space capabilities. When considering war, it is foolish to underestimate an adversary's will or assume to know when or how they would employ their capabilities. Yet this is often the case with regard to U.S. space planners for three primary reasons. First, we assume that we can limit the scale of conflict to such an extent to deny an adversary's use of specific capabilities. Second, we often focus on how an adversary will attack U.S. strengths and ignore our vulnerabilities. Third, we often assume that an adversary will act in a rational manner, and assume they have similar ways of thinking as us. Not only are these assumptions dangerous, they are illogical. As the cost and resources required for entry into space lowers, and as the proliferation of space technologies increases, the threats posed to the United States will continue to increase and we must accept that our "adversaries will likely attempt to harness the same advantages from space the U.S. currently enjoys" (U.S. Army 2014a, 5). In the OE of the future our dependencies and adversary capabilities will change so rapidly that it will be difficult to anticipate operational impacts. While there are actions the United States can take to mitigate these impacts, the dependencies on space can never be fully removed because space has become a critical enabler to both U.S. military and economic power. The truth is that space is no longer a safe haven for U.S. operations, and this fact must be acknowledged. As we move forward into the future, we can expect that space "will be a heavily contested environment, where the U.S. military will have to struggle to secure the information dominance that it simply presumed in the past would automatically obtain" (Tellis 2014, 5). With this understanding of the future OE it is possible to consider the potential impacts to combat effectiveness based on our knowledge regarding the adversary and its counter-space technologies.

a. The Threat

To avoid any misconceptions regarding the term adversaries, adversaries will be defined as those state and non-state actors who have developed "a range of counter-space

capabilities—with both reversible and permanent effects—designed to deny or degrade our ability to conduct military operations and to project power globally" (DOD 2014b, 7). To further delineate the term adversary, any country that the United States currently considers a defense ally, partner, or friendly party will not be considered. With this in mind, the list of potential adversaries can be reduced to just two, Russia and China. It is important to understand that for the purposes of this work, the actual adversary is for the most part irrelevant. The modeling being done in this work sets out to quantify impacts from operations in a D3SOE, and thus does not depend on whom we will face, but rather, it relies only on the potential counter-space capabilities that this adversary can bring to bear. Therefore, it is logical to choose the adversary with the greatest breadth of counter-space capabilities, and to make this determination let us briefly inspect the counter-space capabilities of Russia and China.

Russia has a fairly significant counter-space capability, likely the third most capable following the U.S. and China. This capacity stems from the early years of the space program and through the end of the Cold War, when the USSR and the U.S. were in a long and protracted space race to achieve space superiority. Thus, Russia was able to procure a sizeable combination of counter-space systems and technologies, including everything from GPS and SATCOM jammers to Direct Ascent Anti-satellites (ASAT). Fortunately, a large portion of this technology has fallen into relative disrepair following the collapse of the USSR, and only recently, with the re-emergence of Russia as a world power, has Russia begun to increase its counter-space programs. But even with the re-emergence of Russia, and its renewed effort regarding counter-space capabilities, it will be years before its counter-space capabilities can rival that of the U.S. or China.

Most space professionals consider China as a near-peer space faring nation, with a relatively new and modern counter-space program, which it has matured through a steady increase of resourcing over the last decade. While China's counter-space R&D programs have less of a history when compared to the U.S. and Russian programs, China has been aggressively expanding its space and counter-space capabilities with little friction. In fact, over the last decade "China is developing significant anti-satellite capabilities, integrate cyber into all aspects of military operations, and developing sophisticated

missiles and air defenses as part of an effort to challenge United States' ability to project power" (U.S. Army 2014b, 13). Couple this capability with regional aspirations to expand its influence into the Pacific, an area where the United States also has interest, and it is easy to see why many consider China as the nation most likely to challenge U.S. supremacy and thus, most likely to engage in escalating conflict that could lead to counter-space activities. Thus, due to the potential for conflict, the capabilities, and the willingness to employ such weapons, it is the author's belief that the potential threat from Chinese counter-space capabilities far exceeds that of Russian capabilities, and therefore, open source estimations of Chinese capabilities will be used in this dissertation.

b. Chinese Counter-Space Capabilities

Over the last decade, China has developed a "multi-dimensional program to improve its capabilities to limit or prevent the use of space-based assets by adversaries during times of crisis or conflict" (DOD 2014a, 11), which provides some key insights into the internal thinking of the Chinese. This statement would suggest that the Chinese, who see the United States as heavily dependent on space, have decided that the most likely obstacle to their near-term and long-term national aspirations is the United States. And while many suggest that such a conflict would be detrimental to both economies, which are closely tied, China appears to be preparing for this nonetheless. As China identifies areas where advantage over the United States can be generated, it allocates resources to develop capabilities to leverage this advantage in order to generate combat power. What is most concerning about this is that China seems to have the initiative, and is doing it faster than the United States can respond. This paints a bleak outlook, and based on the expected growth of Chinese counter-space capabilities over the next 10 years, it "ensures that almost every U.S. space component—the space systems in orbit, the links that control them and channel their data, and their associated ground facilities—will face grave perils" (Tellis 2014, 1). The growth of Chinese counter-space activities and programs closely parallels that of the perceived space dependencies described in Figure 7, and in nearly the same proportions. Thus, the Chinese are targeting their counter-space development activities to address the U.S. Space Force Enhancement Missions Areas, specifically SATCOM, ISR, and PNT. Since a large portion of the U.S.

military RCP is derived from the integration of technology and space based capabilities, any success of Chinese counter-space systems in disrupting access to space will have negative impacts on U.S. combat operations. This may result in situations where the U.S. military is no longer able to generate enough combat power to achieve operational overmatch. The means by which China can accomplish this can be seen in Table 1.

Table 1. U.S. Space Systems and Chinese Attack Options.
Source: Tellis (2007, 46).

Table 1. US Space Systems and Chinese Attack Options for Various Missions

	Communications	Early warning and nuclear detection	Intelligence, surveillance and reconnaissance	Meteorology	Navigation and guidance	Remote sensing
Representative US space systems **[orbits]**	Defense Satellite Communications System (DSCS) [GEO] Air Force Satellite Communications (AFSATCOM) and Fleet Satellite Communications (FLTSATCOM) [GEO] Military Strategic Relay Satellite System (MILSTAR) [GEO]	Defense Support Program (DSP) [GEO] Space-Based Infrared System-High (SBIRS-H) [GEO/HEO] Space-Based Infrared System-Low (SBIRS-L) [LEO]	Electro-Optical Imaging Satellites [LEO] Infrared Imaging Satellites [LEO] Synthetic Aperture Radar Imaging Satellites [LEO] Signals Intelligence Satellites [GEO]	Defense Meteorological Satellite Program (DMSP) [LEO] Geostationary Operational Environmental Satellite (GOES) [GEO]	NAVSTAR Global Positioning System (GPS) [MEO]	LANDSAT [LEO]
Feasible Chinese attack options in the near and medium term	Electronic attack Ground attack	Direct ascent attack [LEO] Ground attack	Direct ascent attack [LEO] Directed energy weapons [LEO] Ground attack	Direct ascent attack [LEO] Ground attack	Electronic attack Ground attack	Direct ascent attack Ground attack Directed energy weapons
Feasible Chinese attack options in the long term	Direct ascent attack Co-orbital attack Directed energy weapons	Direct ascent attack Co-orbital attack Directed energy weapons	Direct ascent attack [GEO] Co-orbital attack	Direct ascent attack Co-orbital attack Directed energy weapons	Direct ascent attack Co-orbital attack Directed energy weapons	Co-orbital attack

As shown in Table 1, the Chinese currently have feasible attack options for every one of the U.S. Space Force Enhancement Mission Areas. Depending on the number of counter-space systems used, China has the capability to significantly degrade the operational effectiveness of U.S. forces. This problem will only get worse as China continues to develop new and emerging technologies in the long term, like Co-Orbital ASATs (Co-ASAT) and directed energy weapons, which will increase the quantity and quality of China’s counter-space capabilities as well as the number of systems they can put at risk. Recognizing that any potential US-China conflict would likely take place in

the Western Pacific, the Chinese understand that they have what could be considered the home field advantage. Thus, they understand that the United States will need to rely heavily on space-based systems to overcome the “tyranny of distance” that can negatively impact battle management, command and control, and logistics of U.S. forces. In an anti-access, area denial environment which we expect, a D3SOE will serve to significantly delay a United States response into the Western Pacific, buying China time and space on the battlefield. Thus, as succinctly stated by Ashley Tellis (2014) in his brief to the House Armed Service Subcommittees on Strategic Forces and Seapower and Projection Forces, “the challenges confronting the U.S. military in regard to sustaining the information dominance it has traditionally enjoyed—in the face of current and prospective Chinese counterspace capabilities—will be enormous” (6). Unfortunately, there is currently no way to quantify the expected impacts from such challenges, at least not with respect to operational effectiveness, and thus no way to determine if the United States will be capable of maintaining operational overmatch in a D3SOE. This dissertation seeks to address this shortfall by developing a methodology that can be used to better inform decision support tools with regard to operations in a D3SOE. While this discussion just briefly discussed the counter-space capabilities of China, a more detailed description of the capabilities and impacts of these systems can be found in Appendix B.

3. Know the Environment: Threat Impacts

Most military planners know that understanding yourself as well as your adversaries is critical to making the most informed decisions. But many times the interaction of these two in the context of the OE is overlooked, or viewed as a secondary consideration, yet in many ways it is far more important. Without an understanding of the OE in which the two opposing “Knows”—”Know Yourself” and “Know Your Adversary”—interact, we risk overlooking a large number of potential effects that could impact operations. By considering the U.S. dependencies on space systems as outlined earlier in this chapter, as well as the counter-space capabilities currently available to potential adversaries within the framework of the OE we expect based on the newest AOC, we can obtain a better understanding of the OE and identify expected impacts.

a. *The "New" Operational Environment*

For the first time in well over a decade, the Army has published a new AOC, which captures not only the lessons learned from the past 15 years of combat operations, but also addresses the new direction the Army must take to account for unknown adversaries and an uncertain future. This undertaking is fairly significant for the Army, yet complicated by the fact that "the Army is likewise reducing its end strength and seeking the ways and means to achieve efficiencies while preserving capability and capacity" (U.S. Army 2014a, 3). This AOC is significantly different than past documents for a few specific reasons. First, while past AOCs have addressed a specific threat, the new AOC outlines a future OE that has no specific adversary, no specific threat, no specific AOR, nor any specific tactical organization or mission. Second, the AOC captures for the first time the actual nature of modern warfare, which is highly chaotic and even unknowable. By embracing uncertainty rather than ignoring it, the Army hopes that it can better plan and prepare for the inevitability of operations in an unknown and uncertain future. Unfortunately, this more encompassing view of the OE introduces a fairly significant problem, because not only must the Army assure the nation that it is capable of defeating its adversaries, but it must do so without even knowing who, where, and with what it will be fighting.

To face this problem, the Army has introduced the concept of Integrated Distributed Operations (IDO), which is one of the key tenets of future warfighting as described in the new AOC. IDO calls for the rapid creation and employment of heavily networked force packages and associated support services to quickly address threats. It is the hope of the Army that by maintaining a flexible, interoperable, smaller, and more agile force, that the Army can build tailored force packages that can apply overwhelming combat power at will to achieve decisive victories. Unfortunately, the IDO concept relies heavily on reach-back support for the generation of a large part of its combat power, and thus, "assured access to space capabilities will be critical to the success of the IDO element" (U.S. Army 2014a, 5). The dependency of IDO on space capabilities will affect the success of military operations in a D3SOE, yet the level will be impossible to anticipate because we are currently unable to quantify the impacts of space systems on

operational effectiveness, and thus, the impacts from a D3SOE. This problem is exacerbated by the fact that according to the new AOC, we no longer know the adversary or the systems they will use, which significantly limits our ability to prepare. The problem of planning for an uncertain future is even further complicated because our potential adversaries know exactly who they will fight, how they will do it, and the OE in which this conflict will take place. They will know our dependencies and vulnerabilities, and thus, our adversaries will continue to "invest in technologies to obtain a differential advantage and undermine U.S. ability to achieve overmatch" (U.S. Army 2014b, 11) to degrade the United States ability to project power. This puts us at a significant disadvantage when considering planning and preparation for future operations.

b. Current Threat Assessment

The ability of planners to more accurately plan for and anticipate impacts from adversary actions is a critical component of U.S. military superiority. Because of this, U.S. military operations typically deviate far less from what was planned for compared to our adversaries. Thus, our adversaries are routinely forced to be more reactive in order to recover from this deviation, which allows the U.S. military to gain and maintain the initiative, a significant operational advantage. Unfortunately this is not the case with regard to operations in a D3SOE, because while the U.S. military expects to be significantly impacted during operations in a D3SOE, we currently have no way to accurately anticipate these impacts. With respect to operations in a D3SOE, we are flying blind, forced to make assumptions of potential impacts to operations based on the most simplistic of heuristics. This, coupled with our greater dependency on space compared to any potential adversary, and we see a situation where adversaries can gain the initiative by simply forcing the U.S. military to operate in a D3SOE. To address potential mitigation plans, the United States must consider the requirements of space-based capabilities in the future OE and then assess the vulnerabilities of these systems compared to adversary capabilities. Figure 10 shows the overall risk to U.S. operations due to the interaction of U.S. dependencies and adversary counter-space capabilities.

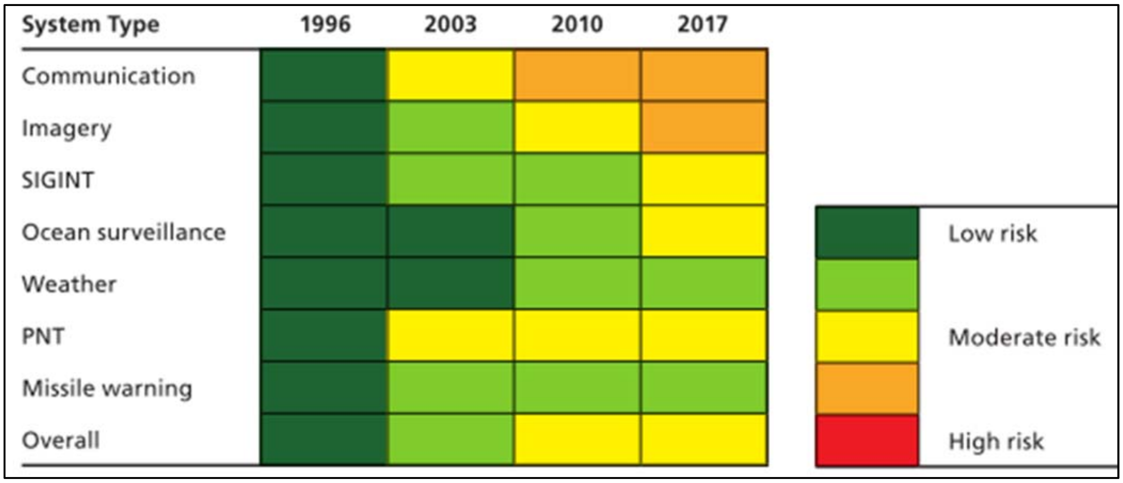


Figure 10. Estimated Risk to U.S. by PRC Counter-Space Capabilities. Source: Heginbotham et al. (2015, 251).

Due to a mix of increased dependencies on space-based capabilities, as well as an increase in counter-space capabilities of China, the overall risk to the United States has steadily increased over the last 20 years. Of these areas, of most concern is the potential risk and impacts to communications, ISR, and PNT. As discussed earlier in this chapter, we know that the United States is heavily dependent on these capabilities, and that adversaries are focusing the majority of their efforts in these areas. But what is most noteworthy is that we do not see any decrease in risk. Thus, while we have long recognized the potential risks from operations in a D3SOE, the data suggests that we have been unsuccessful in mitigating the Chinese counter-space threat. To better understand the potential vulnerabilities associated with this threat we must also consider the potential growth of adversary counter-space capabilities over the near term.

c. Threat Growth

Based on the vision of the future OE as described in the new AOC, we know that the U.S. military can expect to face near-peer adversaries on their own turf, in situations where we will likely be significantly disadvantaged. We also know that to overcome these disadvantages the U.S. military will depend on technology and reach back capabilities to provide the deployed forces with the needed combat power to achieve operational overmatch. Additionally, we have been told that we must do this with a

smaller and more agile force, while maintaining current capabilities. Thus, with respect to the relative number of satellites, use, and perceived dependencies of the United States on space-based capabilities, it is not difficult to anticipate that these will all increase as well. If we expect the United States reliance on space systems to grow under the new AOC, we must also expect that potential adversaries will continue to grow and mature their counter-space capabilities. Thus, we will likely face a future OE where we are even more dependent on space-based capabilities to achieve U.S. national objectives, faced by adversaries who will be even more capable of negating those dependencies. Table 2 provides a simplified assessment of the current counter-space capabilities of China compared to U.S. dependencies, as well as the estimated growth of both over the next 10 years. This assessment, while based on simple assumptions, provides a rough estimate of future capabilities based on historic growth.

Table 2. U.S. Space Systems versus Assumed PRC Capabilities. Adapted from Union of Concerned Scientists (2015).

		US Systems			Current Adversary Capabilities									
	Dependency	# Satellites	Regional Saturation Estimation	US Sats Available	SATCOM Jammers	Low Power Lasers	High Power Lasers	RF Weapons	Particle Beam	DA-ASAT (LEO)	DA-ASAT (GEO)	CO-ASAT	Potential Impact (%)	Total
2015	SATCOM	310	0.4	124	20	0	0	0	0	0	2	1	0.185	0.274
	ISR	80	0.2	16	0	6	0	0	0	4	0	1	0.688	
	PNT	31	0.25	7.75										
	MW	6	0.6	3.6										
	EM	21	0.25	5.25										
	Estimated Growth													
2025	SATCOM	341	0.4	136.4	40	0	4	0	1	0	4	3	0.381	0.543
	ISR	96	0.2	19.2	0	10	0	2	1	6	0	3	1.146	
	PNT	32	0.25	8										
	MW	8	0.6	4.8										
	EM	21	0.25	5.25										
	ISR: Intelligence, Surveillance, and Reconnaissance								SATCOM	ISR				
	PNT: Position, Navigation, and Timing						US Growth		0.10	0.20				
	MW: Missile Warning						Adversary Growth		0.20	0.46				
	EM: Environmental Monitoring													

If current growth trends continue, the overall number of U.S. satellites as well as the number of adversary counter-space systems is expected to grow over the next decade. Unfortunately, the overall risk associated with this expected growth greatly favors the adversary, whose estimated growth of counter-space capabilities more than doubles the growth of U.S. systems. Currently, adversaries can degrade roughly 27% of regional U.S. space capabilities. Yet, within the next 10 years, it will likely be possible for advanced adversaries to degrade over 50% of U.S. space capabilities. While this is based on the

worst case scenario, where an adversary chooses to use all of its capabilities, which is unlikely, it serves to capture a key point…that mitigation through procurement is no longer a viable option. We can no longer presume to be protected by the relatively large number of systems we use, because eventually, the adversary will be capable of degrading all of them, at least regionally. We see this with ISR, where we anticipate that by 2025 that China will be capable of impacting all ISR systems simultaneously within its AOR. If we expand Figure 10 to account for the expected growth discussed in Table 2, we get an even bleaker outlook for future operations when considering Chinese counter-space capabilities as seen in Figure 11.

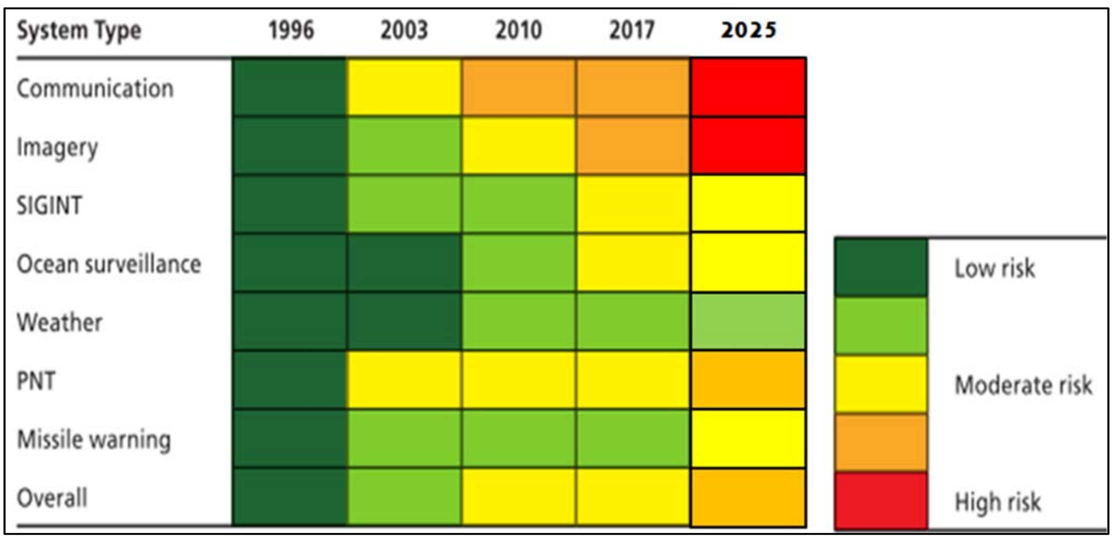


Figure 11. Expected Risk Growth to United States by PRC CS Capabilities. Adapted from Heginbotham et al. (2015, 251).

As can be seen, the overall risk is anticipated to increase from moderate toward high over the next ten years. The majority of the growth in risk comes from the development of adversary counter-space capabilities to counter U.S. SATCOM, imagery, and PNT dependencies, and “the risk to most U.S. space functions appears to be growing faster than the U.S. ability or effort to mitigate them” (Heginbotham et al. 2015, 250). While the point at which the degradation of U.S. systems will begin to affect operational effectiveness is debatable, the impact is not. The U.S. military has become extremely proficient at collecting, processing, disseminating, and acting on information gained from

space; which has allowed us to gain and maintain a tactical and strategic military advantage. We have held this advantage for so long, fine tuning it to the point of near perfection, that any disruption to this system will likely induce cascading effects that we have not anticipated, trained, or prepared for.

B. FRAMEWORK: MITIGATION STRATEGIES AND GAPS

The threat from adversary use of counter-space weapons has been well documented. However, the preparation for such an event has not been executed nearly as well. And while the necessity to prepare for such an operational environment has been codified by the DOD (2012), stating that “the ability to compensate for loss of space capabilities will be integrated into joint and Military Department wargames, simulations, scenario development, experiments, and exercises” (4), the Army’s current mitigation strategies are attempting to address the problem in a piece-meal manner. The fragmented, un-synchronized, and “stove-piped” nature of the current Army space mitigation strategies has led to what can be termed as the “four referents of D3SOE mitigation.” The first of these is the Army combat operations referent, where activities focus on representing the ground combat environment, with impacts being assessed against measures of combat effectiveness. The second of these is the degraded space referent, which focuses on representing systems operating in and through space, as well as the threats they face, with impacts being assessed in terms of strategic and system level MOEs. The third is the mitigation strategies referent, which focuses on the representation of potential mitigation strategies that can address the threats identified from the degraded space environment, typically supporting engineering design M&S. The fourth is the acquisitions of space systems referent, which focuses on representing the operational environment as outlined in key systems engineering documents needed to acquire the mitigation strategies from the previous referent. Figure 12 shows the authors depiction of these referents and their associated interactions. While this is a simple construct, and by no means an attempt to qualify the actual landscape of the four referents, it captures what the author believes to be a lack of a systematic mitigation strategy.

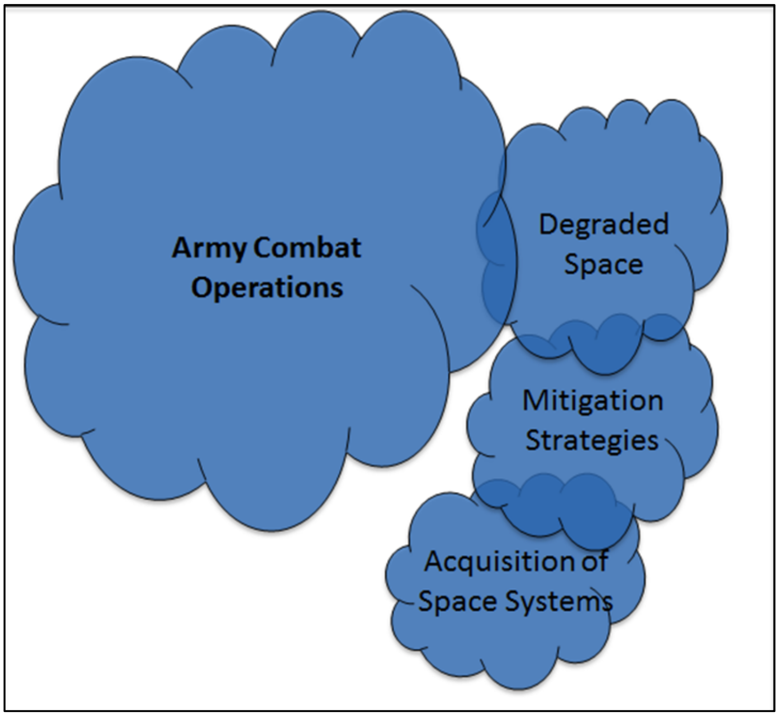


Figure 12. Four Referents of D3SOE Mitigation

It is the author's belief that the stove-piped nature of the Army's D3SOE mitigation strategies has led to significant gaps in the ad hoc strategies that currently exist. From the author's experience, the referents used to support Army combat modeling are quite robust, and adequately represent the majority of the OEs of interest to models. Likewise, the degraded space referent is also fairly robust, and accurately represents the space environment and the interactions of systems within that environment. Unfortunately, the degraded space referent captures only a portion of the combat operations referent, and thus, if used for assessing impacts to operational effectiveness in the combat model, will be incomplete. The same can be said for the operations model, which fails to fully capture the referent of degraded space, and thus, cannot accurately model the impacts from space-based systems. This de-synchronization between the referents only grows as we look at the mitigation strategies developed in response to the understanding of the degraded space referent, which in turn drives acquisition decisions regarding potential mitigation strategies. This is a sequential process, where the understanding of the OE of the first referent is used as the input into the next referent and

so on. Current and emerging Army mitigation efforts typically take place at the overlaps between these referents, addressing the problem at each overlap individually, without the understanding of the full context. While the relative size of the referents in Figure 12 is purely subjective, meant to illustrate the general availability and saturation of these referents within the M&S community, it helps highlight the gaps between the four referents, which results in a de-synchronized mitigation strategy. It is the author's assertion that these gaps are formed due to a lack of operational overlap between the four referents. And while individually these referents are more than adequate to represent the majority of OEs of interest, they are often incapable of accurately representing systems whose actual context resides in the zone of interaction between referents.

By understanding current mitigation trends and the direction in which these emerging efforts are going with respect to the four referents of D3SOE mitigation, we can better highlight the areas where the United States is and is not actively advancing its efforts in dealing with the threat faced from adversary use of counter-space weapons. Because we know that "adversaries will continue to invest in technology to counter or evade U.S. strengths, resource reductions and insufficient force modernization place at risk the U.S. ability to overmatch its opponents" (U.S. Army 2014b, 41), the United States must take a more synchronized approach to mitigating the impacts from a D3SOE than in the past. The first step in this process is to address current mitigation efforts, and by doing so, it should be possible to fully identify and understand the capability gaps with regard to an adversary's counter-space threats, as well as to help inform decisions regarding the allocation of resources. This section will identify areas that the United States has demonstrated a desire to advance its efforts to prepare, which usually take one of three forms, Doctrine, Technologies, or Modeling.

1. Doctrine

To better prepare for the potential operational activities, the Army relies heavily on the development of doctrine to codify how it will respond to a given number of potential situations. Typically, this doctrine takes two primary forms: TTPs and Policy. And while doctrine can never account for every possible problem or dictate a perfect

solution, it does help the Army prepare for likely situations. As highlighted in the National Security Space Policy (DOD 2011a), doctrine which has sufficient detail, to include means of implementation, can drastically improve the preparation for operations in a D3SOE. Figure 13 depicts where the Army is currently addressing mitigation strategies with regard to doctrine.

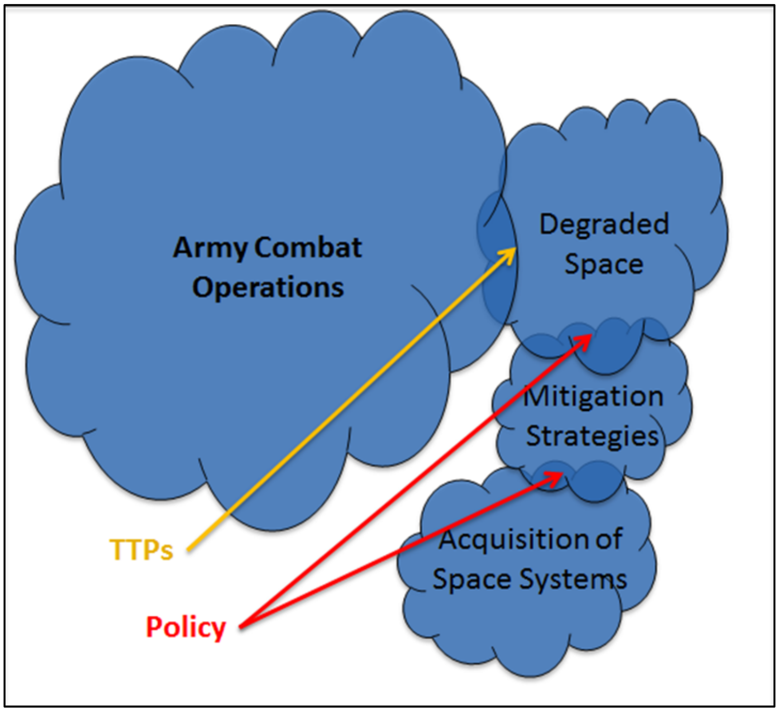


Figure 13. Mitigation through Doctrine

TTPs and Policy are applied at all three of the overlaps between the four referents of D3SOE mitigation, but are not mutuality supporting. While all overlaps are covered in one way or another, mitigation through doctrine fails to synchronize both TTPs and Policy at each of the three overlaps. TTPs tend to focus at the operational and tactical levels, giving direction to lower level units in preparation of combat operations, but this preparation cannot be limited to codification in national doctrine, it must "extend to the people and processes relying on space information, operating our space systems, and analyzing space-derived information" (DOD 2011a, 11). To do this effectively, Army forces must have trained and exercised in this environment, and the TTPs learned in that

process must be codified and documented in every unit's standard operating procedures. While these TTPs cover only a small fraction of potential threats from operations in a D3SOE, they provide some basic capability for mitigation. Policy tends to focus at the strategic level, giving direction to higher level units during tasks like planning and acquisitions. The purpose of policy is to define the high level guidance of the United States, and provide a foundation for other efforts of the United States Government (USG) to prepare for operations in a D3SOE. While policy exists, the implementation for much of it has not kept up with changing technology, and thus, the United States has been slow to develop adequate means in which to deny adversary gains from use of its counter-space weapons, leaving the overall approach of mitigation vulnerable to exploitation.

2. Technologies

Technology is the key to implementing new and innovative mitigation strategies of the future. In the coming years, the Army will depend on these technologies "to help set the theater, surge capabilities for network and sensor assets, augment challenged space architectures, and reconstitute capabilities and forces after adversary actions have damaged or impaired space capabilities" (U.S. Army 2014a, 6). Through the creative application of technologies to address mitigation strategies identified in policy, the Army stands the best chance for preparing for operations in a D3SOE and maintaining the capability to fight and win in a complex world. While U.S. doctrine attempts to addresses the overall guidance that drives the development of mitigation strategies as well as some political maneuvering to reduce risk, doctrine in itself is not a complete solution. To truly implement a comprehensive mitigation strategy, technological solutions will always be needed. For the United States to be successful, it must be able to "defend friendly access to space capabilities, and ensure mission command access, by defeating or disrupting adversary attempts to deny, degrade, and destroy Army and joint access to space-based systems" (U.S. Army 2014a, 6). To do this effectively requires a combination of both Doctrinal and Technological strategies. Doctrinal strategies provide the logical "ways," while technological strategies provide the physical "means" in which the mitigation strategies can be enacted. Figure 14 shows where most technological mitigation strategies are currently addressed.

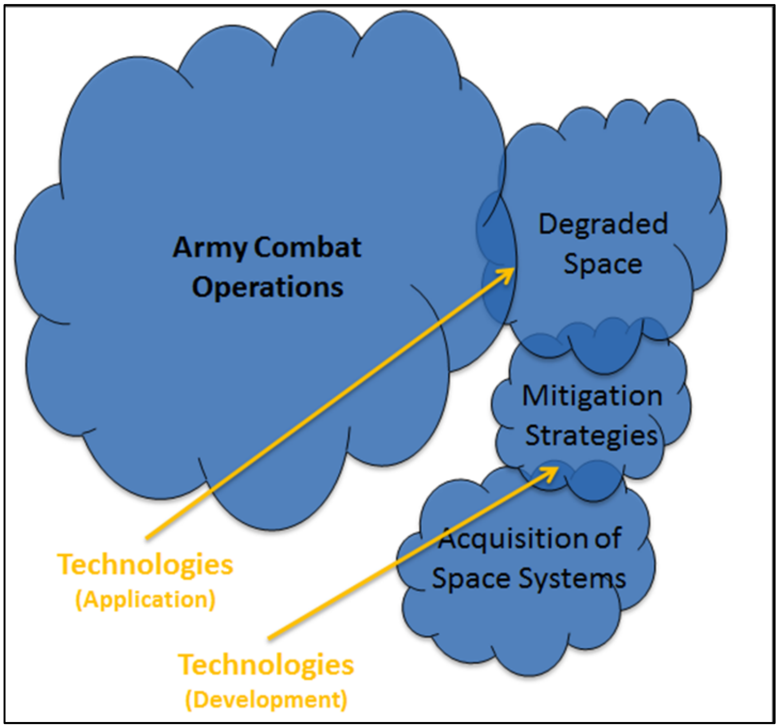


Figure 14. Mitigation through Technology

As shown in Figure 14, technologies are typically developed at the overlap between the mitigation strategies and acquisitions referents, though the technology itself will be applied at the overlap between the degraded space and combat operations referent once fielded. Thus, technological solutions developed and acquired to address mitigation strategies are done absent from direct input from the degraded space and combat operations referents, i.e., solutions are developed using a different understanding of the OE from the one in which the solution will operate. This is a type I error, and primarily due to the fragmented and unsynchronized manner in which the Army currently addresses mitigation strategies. Thus, while technology is developed to mitigate the risk and impacts from operations in a D3SOE, it is done so with an incomplete understanding of the OE, and absent an understanding of the full operational referent, will likely produce solutions that fail to meet their operational objectives.

3. Modeling

The integration of M&S in the DOD has led to significant advancements over the past two decades, primarily in computing technologies that have drastically increased modeling capacity and applicability. Army M&S activities primarily support decision making in the R&D communities, but also support operations, planning, and training as well. The use of M&S has “become ubiquitous and indispensable to the Army as vital enablers of the Generating and Operating Forces” (U.S. Army 2017) and is a valuable tool for assessing the feasibility of mitigation strategies. To support a well-executed and informed MDMP and COA development, the Army uses a host of modeling tools and software packages that allow planners to better visualize and understand the OE. When aggregated, the outputs of these models provide a detailed and in-depth understanding of the interactions of the opposing forces within the OE. The majority of all combat systems and their individual contributions to RCP are well defined, including everything from a single soldier to a Battalion (BN) of tanks. These definitions often include variations to account for different sets of conditions like terrain and weather, which can all be accounted for during the MDMP. Unfortunately, as George Box (1987) famously said, “all models are wrong; the practical question is how wrong they have to be to not be useful” (74). The Army understands this dilemma, and rather than focusing on the production of answers to threats that are based on an inaccurate model, the Army instead seeks to use M&S to gain insights into the impacts from operations in a D3SOE.

Within the Army space community there are four primary referents used to support M&S to gain the insight needed to support decision making; all of which have some impact on the Army’s ability to mitigate risk from operations in a D3SOE. The first is Army combat operations, where M&S can be used to support operations assessments and planning of mitigation strategies. The second is the modeling of degraded space, where M&S are used to model the impacts of a D3SOE on operations. The third is the modeling of potential mitigation strategies, where emerging systems and concepts can be tested for operational utility. And the fourth is M&S in support of acquisitions of space systems, where M&S tools are used to inform the acquisitions process of mitigation

capabilities. A depiction of how M&S is applied to the four referents of D3SOE mitigation can be seen in Figure 15.

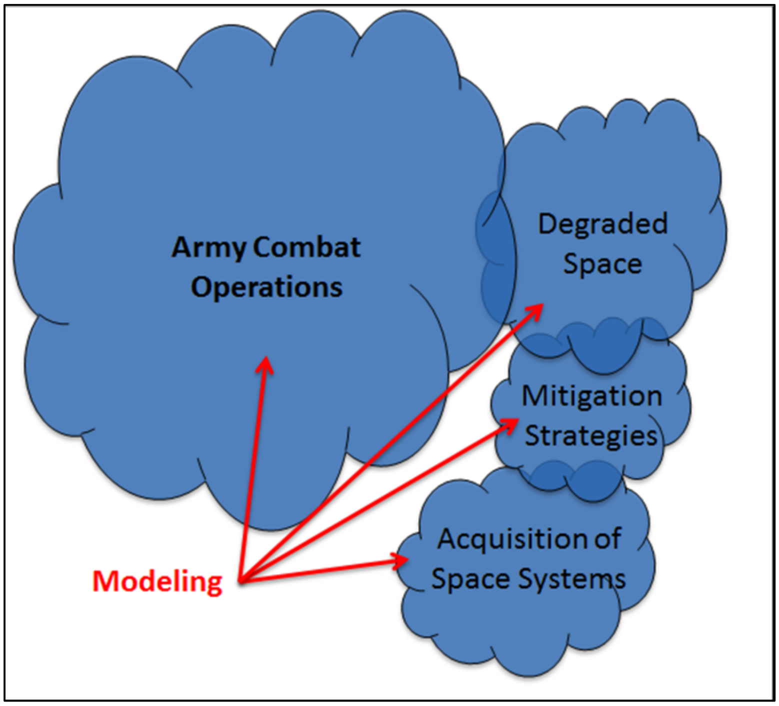


Figure 15. Mitigation through Modeling

Army M&S activities are not focused at the overlaps between the four referents of D3SOE mitigation as we saw with doctrine and technology, but rather, because these referents are the foundation from which the individual M&S activities develop their models, they focus on capturing the specific referents of interest. This is a contributor to the inability of current practices to support the modeling of a D3SOE. To do so would require a shared understanding (referent) of the actual OE, and currently, M&S activities in each of these areas of D3SOE mitigation tend to be stove-piped, deriving their understanding of the OE from its own specific referent with little or no understanding of the other ones. The unsynchronized nature of current modeling practices is primarily caused by the issue of complexity in models. Because most models are developed for a specific reason to address a specific problem set, the resolution and detail of these models are typically maximized in the areas of interest, depending on the intended use. Thus,

areas of less interest, like the OE of the other referents, are modeled at a lower fidelity, if at all. The Army's current use of models with respect to mitigation in each if the four referents of D3SOE mitigation will now be discussed.

a. Army Combat Models

The Army has a large contingent of combat models and can model ground combat operations to a high level of detail. Current combat models like COMBATXXI, OneSAF, and AWARS fill numerous operational support roles by providing key analysis across the operational domain where this information can help support decision making. COMBATXXI is the premier combat model currently in use by both the Army and Marine Corps and is likely the most complex and detailed model ever built by the Army. While this level of complexity makes it well suited for accurately capturing the environment for which it was designed (combat operations), it also limits the combat model's ability to addresses other modeling referents, like operations in a D3SOE. It is important for model users to understand that due to the growing complexity of Army combat models, most models only consider the referents for which they were designed. With regard to the four referents of D3SOE mitigation, this means that combat models, nested in the combat operations referent, do not consider the impacts from the OE of the other referents. Thus, decisions made regarding mitigation strategies based on a combat model will not be accurate, because they largely fail to account for the actual OE, which includes a host of ESINQ effects, to include space-based effects.

b. Modeling Operations in a D3SOE

The modeling of operations in a D3SOE is often only a secondary consideration when compared to the modeling of combat operations. When coupled with the Army's stove-piped manner of model development, Army models typically have a limited ability to account for operations in a D3SOE. Luckily, Air Force models can model space-based capabilities and the space environment fairly accurately. SEAS for example, is an Air Force combat model that is by far the most capable of all models investigated during the execution of the MSSSM with regard to modeling a D3SOE. Yet, similar to COMBATXXI, it also has some shortcomings due to its complexity. As with

COMBATXXI, SEAS looks to reduce model complexity by disregarding aspects of the OE to account for areas of interest. With regard to SEAS, an area overlooked was the ground combat segment, which is understandable when considering its purpose as an Air Force space model. Thus, as we saw with Army models, decisions made regarding mitigation strategies based on a space model will not be accurate, because they fail to account for all the interactions and dependencies between ground and space operations.

c. Modeling of Mitigation Strategies

To reduce the risk from the inherent inaccuracies of the information supporting decision makers, the modeling of potential mitigation strategies often focuses on standalone solutions for specific threats, thereby minimizing the chances of compounding inaccuracies. The relatively narrow scope of these targeted solutions creates an inefficient developmental environment which tends to ignore both positive and negative impacts from outside of the system boundary. This “stove-piped” approach to development tends to generate solutions driven by system level MOPs, constraints, and limitations rather the higher level MOEs and their impacts to metrics of operational effectiveness. These issues are compounded by the fact that both the Army and the Air Force address the development and modeling of potential mitigation strategies from different perspectives. The Army focuses on mitigation strategies that are tied to tactical MOEs, while the Air Force is concerned with higher level strategic MOEs. Unfortunately, the tactical and strategic MOEs are typically disjointed, and do not translate well from one to the other. While this current method of mitigation may work at times, it is by nature inefficient, and fails to take full advantage of the potential utility that could be gained by synchronizing a more formalized mitigation strategy. Thus, as we saw before, decisions made regarding mitigation strategies based on these constrained and incomplete referents will not be accurate, because they largely fail to account for interaction between the combat and degraded space OE.

d. Modeling in Support of Acquisitions

The Army’s current use of M&S in support of acquisitions is fairly well documented, yet with regard to the acquisitions of mitigations strategies, the process

becomes complicated. While the Department of the Army (DOA) (2011) has made it clear that acquisition program managers will use M&S to augment activities with the goal of increasing capabilities while minimizing cost and time, the sequential and widely distributed nature of the four referents of D3SOE mitigation makes it difficult to apply a synchronized strategy with regard to acquiring mitigation strategies. Modeling efforts in support of the four referents of D3SOE mitigation typically focus on assessing the contributions of alternative mitigation strategies in an effort to select the strategy or strategies that provide the most utility to the warfighter. Unfortunately, this assessment is typically based on the OE used by the acquisitions model, whose referent is only loosely based on combat operations in a D3SOE. Making accurate acquisitions decisions based on these inaccurate models is even further complicated by the breadth of acquisition activities in the DOD, which not only differ between each service but within them as well. Thus, as was seen before, due to the segregation of the four referents of D3SOE mitigation, their inability to capture the referents of the other OEs, as well as the differing objectives of the individual services, synergizing the acquisitions of accurate and well nested mitigation strategies is extremely difficult.

4. Organizational Modeling Gaps (Army/DOD)

While the current and emerging mitigation techniques described in this section, which included Doctrine, Technology, and Modeling, are steps in the right direction, the capabilities of the threat counter-space arsenal continue to increase. Whether current or emerging United States mitigation strategies will succeed in deterring aggression and protecting our space systems is yet to be seen. And as Heginbotham et al. (2015) described, the U.S.'s preparation for operations in a D3SOE "will depend on what investments the United States makes in space defense in the coming years and whether it can find ways to reduce its systems' vulnerabilities" (257). Thus, the U.S. military must accelerate its efforts to anticipate adversary counter-space activities. While this will likely require a significant investment in resources as well as an increased focus from leadership, the DOD must be proactive in preparing for operations in a D3SOE.

Unfortunately, the Army has not thought it necessary to put forth the resources needed to fully investigate and quantify the contributions of space-based capabilities to RCP. Nor are there adequate modeling tools or software packages available to support the level of analysis needed. While "space modeling-and-simulations will be needed increasingly to support mission planning and rehearsal activities" (U.S. Army 2014a, 9), they do not currently exist in any form usable for space mission planners. While Army models do a fairly good job at representing the combat environment, they often aggregate and ignore secondary and higher-order interactions within the model to reduce complexity. Unfortunately, this aggregation typically takes place where many ESINQ systems and effects reside, and has resulted in an inability of current models "to represent the impact of new forms of command and control on combat outcomes because they are all based on physical models of attrition" (Cares 2004, 4). Thus, the Army finds itself in a situation where there are no M&S packages capable of accurately modeling the impacts of space-based capabilities on ground operations, the primary reasons for which fall into three broad categories.

a. Desynchronized Mitigation Strategies

The Army does not have the ability to accurately model dependencies on or the impacts from space-based systems, nor does it have a model to accurately compare and analyze different mitigation strategies. Even the Air Force, which can model mitigation of a D3SOE better through SEAS, fails to adequately tie its outputs to measures of operational effectiveness of the ground force. Thus, decisions and recommendation for the development of emerging mitigation strategies of both the Army and Air Force tend to have little-to-no traceability to actual measures of operational effectiveness, and fail to capture the actual OE. Due to the lack of traceability, the models used to inform decision makers regarding potential mitigation strategies typically only consider the requirements to acquire the strategy and are not well nested with either the D3SOE or the combat OE. Figure 16 shows the 1st order gaps within the four referents of D3SOE mitigation.

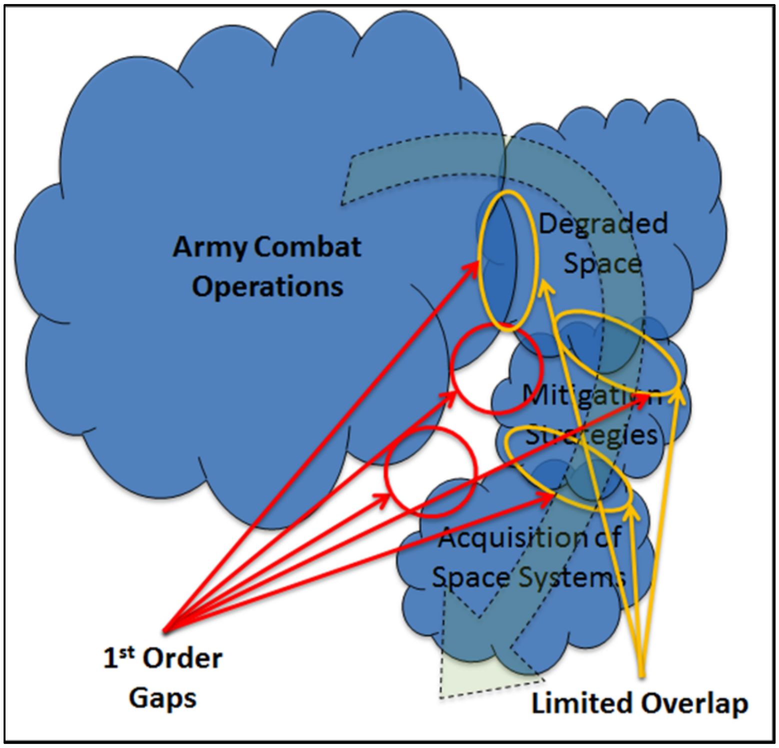


Figure 16. Gap Analysis: 1st Order Systems

As shown in Figure 16, the Army tends to focus its modeling efforts in support of D3SOE mitigation on just four referents of D3SOE mitigation. The lack of overlap between these referents has resulted in an inaccurate assessment of the OE from one referent being passed to the next referent. This work defines these as 1st order gaps, which deal with the failure of each of the four primary referents of D3SOE mitigation to maintain traceability to the actual OE. These gaps can take two forms: complete gaps where no overlap exists, which are represented by red circles, and limited overlap gaps, which are denoted by yellow ovals. Starting with Army combat operations, one can see that there is little overlap with degraded space modeling, which is primarily an Air Force requirement. Thus, Army combat models fail to capture the space environment in the detail needed to represent space dependencies and threats, and Air Force degraded space models fail to capture the ground environment in the detail needed to assess operational impacts. Similar phenomenon can be seen at the other overlaps as well. The modeling of mitigation strategies receives only a partial understanding of the degraded space OE, with no direct consideration for the OE from combat operations. Likewise, acquisition of

space systems also fails to directly account for the combat operations OE, with only a partial understanding of the mitigation strategies OE. This sequential approach results in each of the focal referents of D3SOE mitigation having its understanding of the OE informed through only a partial understanding of preceding referent. Thus, like all sequential systems, errors are aggregated and passed along, resulting in decisions that are not directly tied to either the combat environment or the D3SOE environment.

The impact of a sequential process can be best illustrated by considering the four referents of D3SOE mitigation as children playing telephone. The first child, the combat model, informs the D3SOE model, but because of the limited overlap of the two, an incomplete understanding of the OE is passed. The D3SOE model then informs the modeling of mitigation strategies, but again, due to the limited overlap of the models, an incomplete understanding of the OE is again passed; only this time the error has been compounded. Lastly, the mitigation strategy model informs the acquisitions model and due to the limited overlap between the two, again provides an incomplete understanding of the OE. Therefore, the understanding of the OE that the acquisitions models use have little traceability to MOEs of the ground combat model, which according to proponents of Operational Effectiveness Modeling (OEM), is the primary measuring stick from which all decisions should be made. Thus, mitigated strategies are assessed using a skewed understanding of the OE, which fails to meet a key tenant of MBSE, which is to allow the systems' impact to operational effectiveness be the primary drivers of design.

To rectify this issue we need to develop systems whose purpose has traceability to combat effectiveness metrics, rather than the system-level MOPs that are typical of most sequential development approaches. To do so, we must scrap the sequential approach to problem solving and replace it with a more all-encompassing method for assessing gaps. While a sequential process can lead to a general increase in system level capability without consideration for MOEs, bigger is not always better: and MOPs like increased bandwidth and increased collection capability are not directly correlated to MOEs of improved combat effectiveness. Additionally, this type of approach is no longer justifiable in the current resource restrictive environment, which often requires metrics that can better quantify the return on investment. This goal is possible through a

capability-based decision and design methodology, which can consider the 2nd order gap as shown in Figure 17.

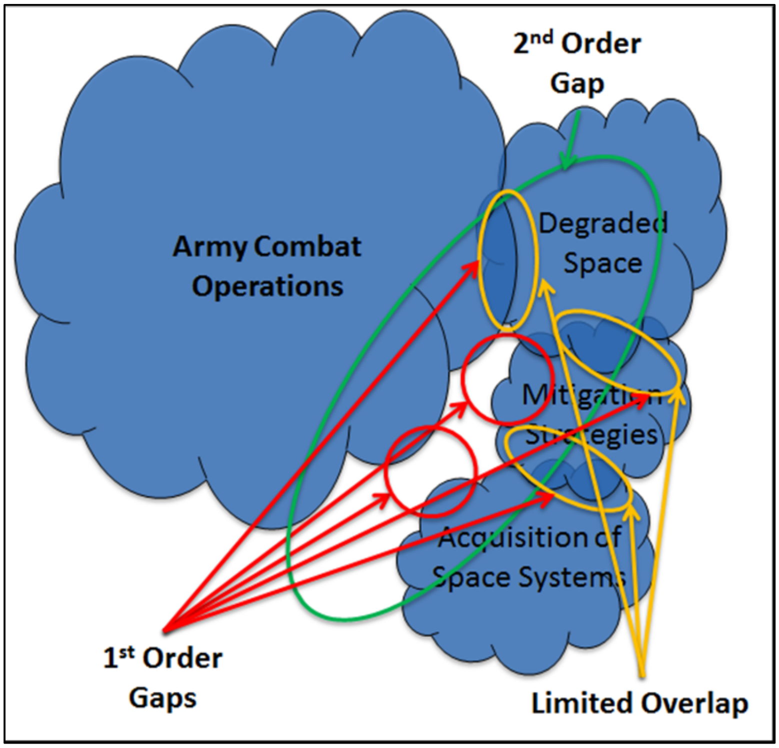


Figure 17. Gap Analysis: 2nd Order Systems

As shown in Figure 17, the 2nd order gap captures all of the 1st order gaps by using a broader and more encompassing methodology that can better account for the actual OE, which negates the flawed sequential process of 1st order systems in lieu of a more robust and synchronized problem solving process. Simply put, 2nd order systems consider the OE of all four of the referents of D3SOE mitigation simultaneously as well as their higher level interactions with external systems and associated MOEs. By attacking the problem in this more holistic manner, we can more accurately account for the operational impacts from adversary use of counter-space weapons and therefore, more accurately predict the capabilities of emerging mitigation strategies. Unfortunately, the ability of decision makers to account for the 2nd order gap is significantly limited because current

methodologies and tools are not well suited for addressing the effects of external systems and non-quantifiable or intangible factors.

b. Service Model Divergence

While Army models like COMBATXXI, OneSAF, and AWARS do an excellent job of modeling ground combat operation, they capture only a fraction of the air and space referent, typically capturing just a few of the more rudimentary effects. Alternately, while Air Force models like SEAS, AFSIM, and SCT can model space and space-based capabilities in great detail, they do not model ground operations to the level of resolution needed to support the Army, nor do their MOEs translate to MOEs from the perspective of the Army. Thus, there is currently no M&S package that can accurately model the impacts of space-based capabilities on the ground force, because no one has attempted to build a cross-domain model whose referent accurately captures both domains. A graphical depiction of this divergence can be seen in Figure 18.

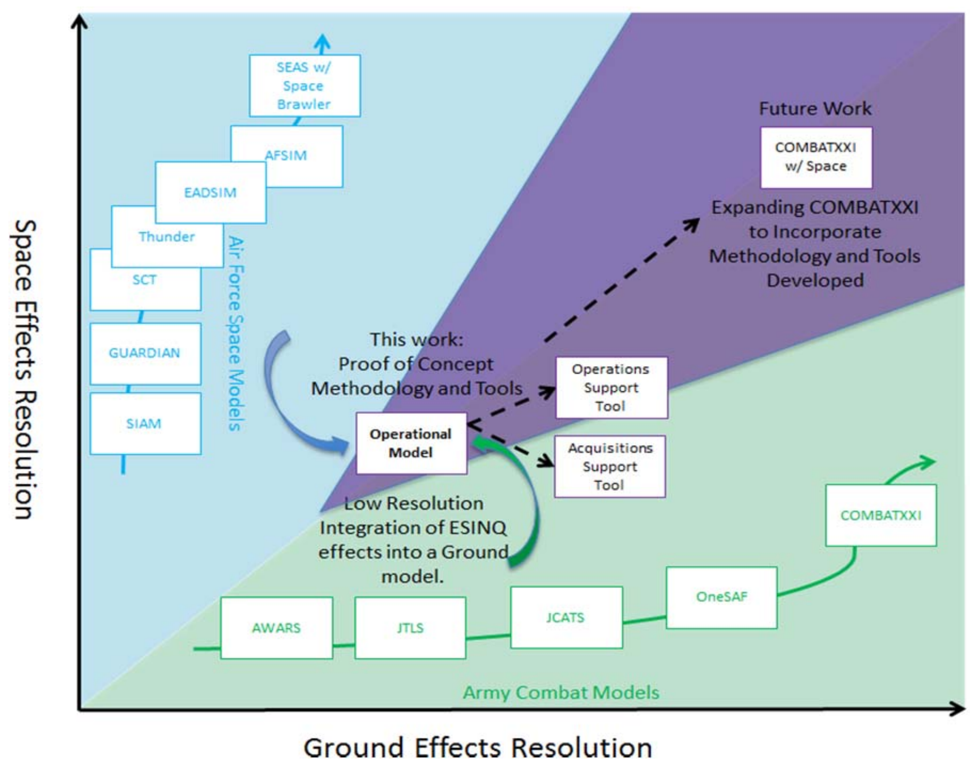


Figure 18. Ground and Space Modeling Divergence

As shown in Figure 18, both Army and Air Force models continue to increase in resolution/complexity, but primarily in the domain in which the models were designed. Thus, they continue to diverge from each other, increasing the desynchronization of the individual referents and moving further away from the model that is needed by Army space planners. In an attempt to resolve the disconnect, this dissertation will use the IMDP to capture the key elements of a D3SOE within a low resolution Army model to bridge the gap between Air Force and Army models. This proof of concept will provide decision makers a more robust and accurate model for operational and acquisitions decision support, while providing future model development efforts a framework for expanding models to account for cross domain effects.

c. *Modeling Domain Segregation*

Counter-space systems present a significant threat to the United States' freedom of maneuver, and "to prevent enemy overmatch, the Army must develop new capabilities while anticipating enemy efforts to emulate or disrupt those capabilities" (U.S. Army 2014b, 11). Yet the DOD does not currently have a dedicated cross domain M&S package that can effectively evaluate these new capabilities. Current DOD M&S methods still favor large and complex models that accurately model very specific domains, which can best be described in Figure 19.

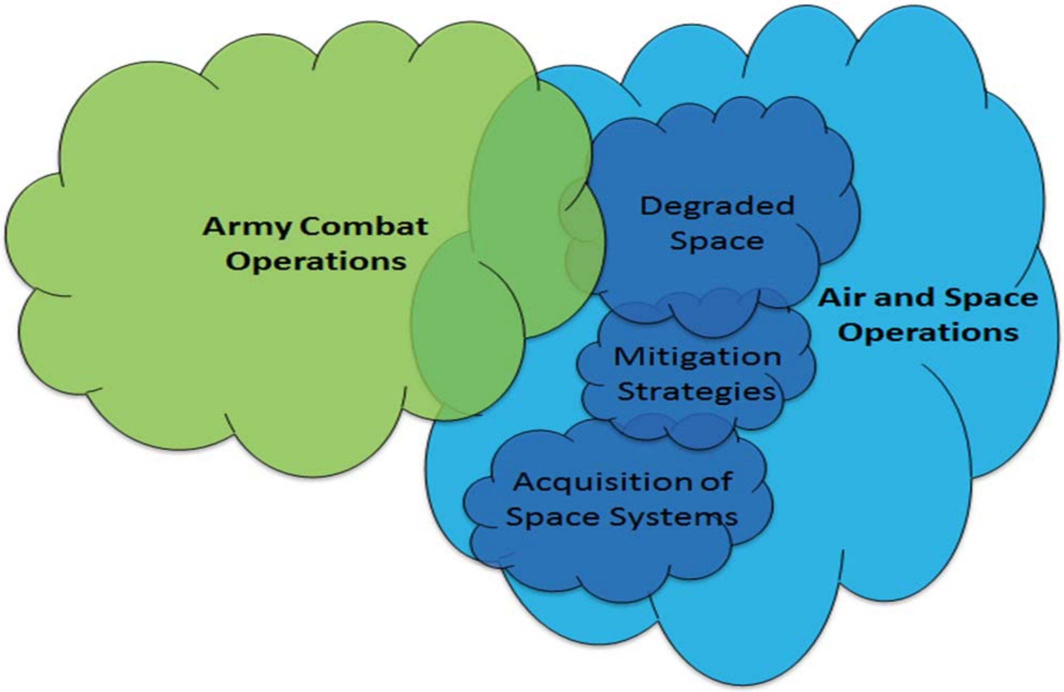


Figure 19. Modeling Domain Segregation

Figure 19 is the author's representation of the segregation of modeling within the DOD. Army models focus on the ground domain, Air force models focus on the air and space domains, to include responsibilities for degraded space and acquisitions of space mitigation strategies, with neither model being able to do them both well. There are three major issues with acquiring mitigation strategies in this manner.

1. Desynchronized referents of the services. Due to the limited overlaps of the service referents, any acquisitions process that produces a system to support the Army will do so with only a partial understanding of the Army ground combat referent.

2. Differing domains of operations. Systems produced using primarily Air and Space operational domains will not perform as intended when assessed in the ground domain.

3. MOE translation. Systems designed and acquired by the Air Force will have a different set of MOEs than the MOEs of interest by the Army; Air Force strategic MOEs do not translate well to Army operational MOEs.

While models will continue to support the design, assessment, and acquisitions of systems, to include mitigation strategies, models do not seem to be evolving in parallel to

the changes we are seeing in policy and technology. When compared to both doctrine and technology, modeling has made the least progress with regard to preparations for operations in a D3SOE. And while models are flexible to change, this is only true to the point where it starts to impact its usability. There is a ceiling to model development, where no more complexity can be added without compromising some other aspects of the model. It is because of this ceiling that most models aggregate or ignore the effects of space-based capabilities on operations. Models are developed for a reason, and unfortunately, none of the current models used in the Army were designed to look at the impacts from operations in a D3SOE. While some models, like COMBATXXI, were designed to represent degraded BMC2, these aspects of the architecture were not exploited very well, though with the ongoing work of developers to represent behaviors, they could be in the future. To improve the acquisitions process of mitigation strategies and to produce systems that can provide more utility to the warfighter, a methodology is needed that can better link the Army and Air Force modeling referents. Until policy directs the development of a cross-domain model, one capable of modeling the impacts of external and context systems on ground combat operations, users will be forced to find unique and creative ways in which to use non-optimal models to assess ESINQ effects.

(1) Modeling in Support of Operations

The focus of Army planners is to support the overall COA development process by providing an assessment of the relative combat power. By definition, "Relative combat power analysis involves assessing tangible factors (such as, equipment, weapon systems, and units), and intangible factors (such as, morale and training levels)" (DOA 2005, 3–30). Thus, for space planners, the focus should be on comparing friendly and enemy space assets, to include all potential sources of space-based force enhancement, like commercial assets. Unfortunately, the comparison of RCP of opposing space capabilities relies on the simplest of heuristics and qualitative assessments, giving space planners little quantifiable information to support decision making. While the Army MDMP and its supporting tools are well suited for assessing tangible factors, they do not account for intangible factors, and typically ignores space and counter-space intangibles altogether. The most common operational planning tool currently in use by the Army is

the FRC, which is based largely on the work of Ronald Misak (2001), who in his thesis work used the Army's Consolidation of Forces Model (COFM) to attempt to quantify the contributions to operational effectiveness from specific forces.

Unfortunately, as Zanella (2012) noted in his thesis work, the FRC has some significant shortcomings. First, the model has not been updated since 2001, when it was developed to focus on soviet-era tactics and threats, and thus, it is outdated and no longer represents current Army doctrine or modern OEs. Second, of the eight doctrinal sources of combat power (leadership, information, mission command, movement and maneuver, intelligence, fires, sustainment, and protection), the FRC is only capable of capturing two of them, fires and protection, and completely ignores the rest, likely due to being considered as ESINQ factors and effects. As noted by Zanella (2012), these "factors are traditionally ignored by modelers in equations because they are extremely difficult to quantify and replicate" (30). Third, combat power is additive, using a simple system versus system comparison, with no consideration for the synergistic effects of combined arms operations. Fourth, it does not account for force structures below the BN level. All in all, these failures typically lead to the consistent underestimation of friendly force combat power by the FRC, which routinely recommends a larger force than is actually needed. Thus, the Army's current process ignores intangible or non-quantifiable factors during RCP analysis, when these intangible factors likely represent the majority of the sources of total combat power. Ignoring ESINQ factors like space-based capabilities is a fault of the MDMP, especially because they can often be just as important to the generation of combat power as the tangible factors. This concern is one of the key motivators of this dissertational research. The improvement to the MDMP through the quantifiable assessment of ESINQ capabilities will produce a more accurate representation of the OE and garner better and more informed decisions.

(2) Modeling in Support of Acquisitions

Similarly to modeling in support of operational planning, DOD Space Acquisitions typically uses some amount of M&S software to support decision making. Unfortunately, like operational planning, this support has been based on tools that do not accurately account for intangible factors like space and space-based capabilities.

Consequently, the Army Space community has had a poor history regarding the success of its space R&D programs, suggesting a potential linkage. It is the author's assertion that the high failure rate of Army space R&D programs can be attributed to a lack of analysis during the early phases of the acquisitions process. Specifically, the author believes that this lack of early analysis is due to the failure to consider the potential contribution of new and emerging space capabilities to metrics of operational effectiveness of the force, imbedded in an accurate assessment of the OE. In the resource restricted environment of today, resources should be allocated to programs based on merit, specifically on how well a program contributes to the generation of RCP.

Unfortunately, the ability of Army space acquisitions professionals to execute the type of analysis needed to quantify operational effectiveness is complicated by two primary factors. First, the Army space community considers its space programs as R&D and thus not subject to the same oversight and restrictions as programs of record. Without a more informed and formal approach to the allocation of resources to emerging programs, the Army Space community will likely continue its poor record of performance. Second, as we saw with operational support, there is currently no way to quantify the contributions of space-based capabilities to the warfighter. The inability to quantify these contributions is primarily due to the fact that there has been neither the need, the priority, nor a model capable of accurately modeling space enabled ground operations. One must ask, could space acquisitions professionals make better decisions regarding the allocation of resources if they had access to a tool that allowed them to analyze the tradespace of emerging space systems and compare each system's ability to contribute to the RCP of the ground force? The author believes so, and a major intent of this dissertational work is to address this gap by providing Army acquisitions space professionals with a methodology and a set of tools that can better represent the contribution of U.S. space dependencies on operational effectiveness, as well as the impacts from adversary use of counter-space capabilities.

C. KEYSTONE: M&S COMMUNITY MODELING GAPS

As we saw in the previous sections, the manner by which the Army mitigates threats from operations in D3SOE can be considered "stove piped." By binning mitigation strategies into doctrine, technologies, and modeling, most strategies are developed to solve only a specific problem within a narrow view of the overall OE, without consideration for parallel and higher-level efforts. While this method can provide individual solutions for specific threats, it cannot fully capture the impacts from operations in a D3SOE because the models used cannot fully account for the operational dependencies of the ground force on ESINQ capabilities. The Army's focus on high resolution combat models like COMBATXXI has complicated this problem even further because the requirements for these ground-centric models do not include dependencies on space-based capabilities. Without these dependencies, it is impossible to build an accurate representation of the OE, which has left most Army M&S packages less than optimal for addressing impacts to operational effectiveness in a D3SOE. Decisions made based on the output of limited models are inherently risky because they are based on incomplete knowledge. While the Army has been fairly successful in identifying and addressing the necessity to mitigate potential threats, it has been unsuccessful in mitigating them, primarily due to the turmoil that currently exists within the DOD M&S communities as well as a lack of a means to accurately quantify the impacts they may have on combat operations. This turmoil can best be described in Figure 20.

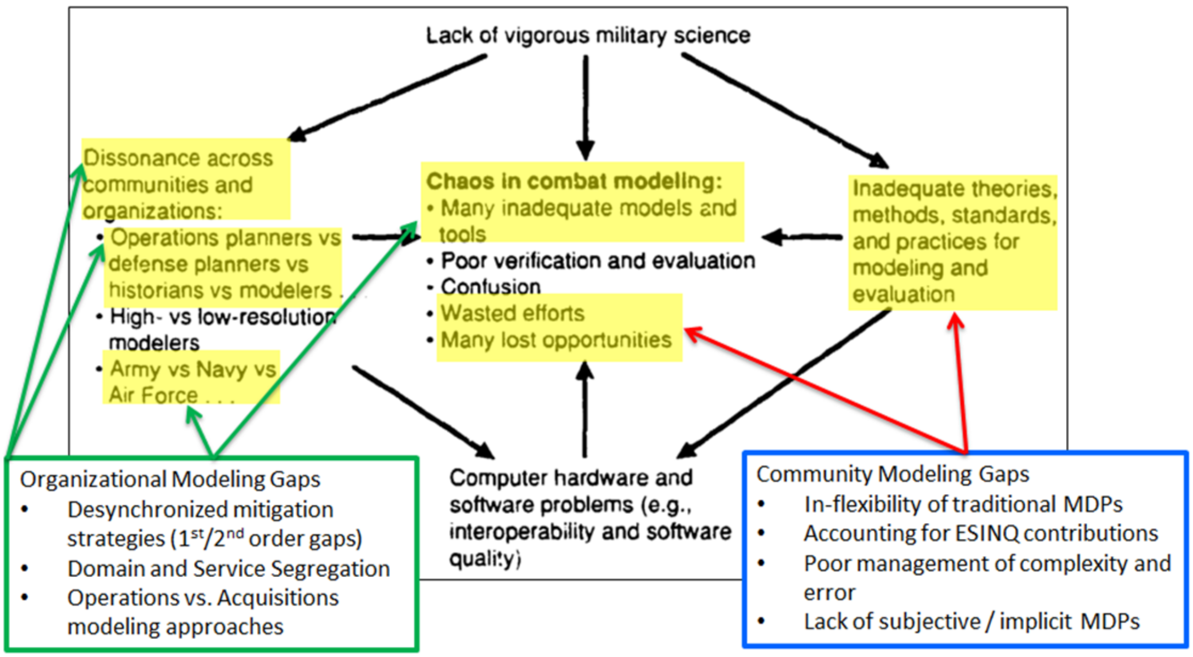


Figure 20. Gaps and Modeling Chaos.
Adapted from Davis and Blumenthal (1991, vi).

According to Davis and Blumenthal (1991), multiple issues within M&S practices contribute to the chaos in combat modeling, which has left us with inadequate tools and processes to address current and emerging threats. As shown, Figure 20 captures all three of the observed organizational gaps discussed in the previous section, and highlights many potential gaps at the M&S community level. To link the observed Army operational modeling gaps to an overarching higher level M&S community modeling gap that could be filled to address the observed gaps at the organizational level, gap analysis was conducted, the traceability matrix for which can be seen in Figure 21.

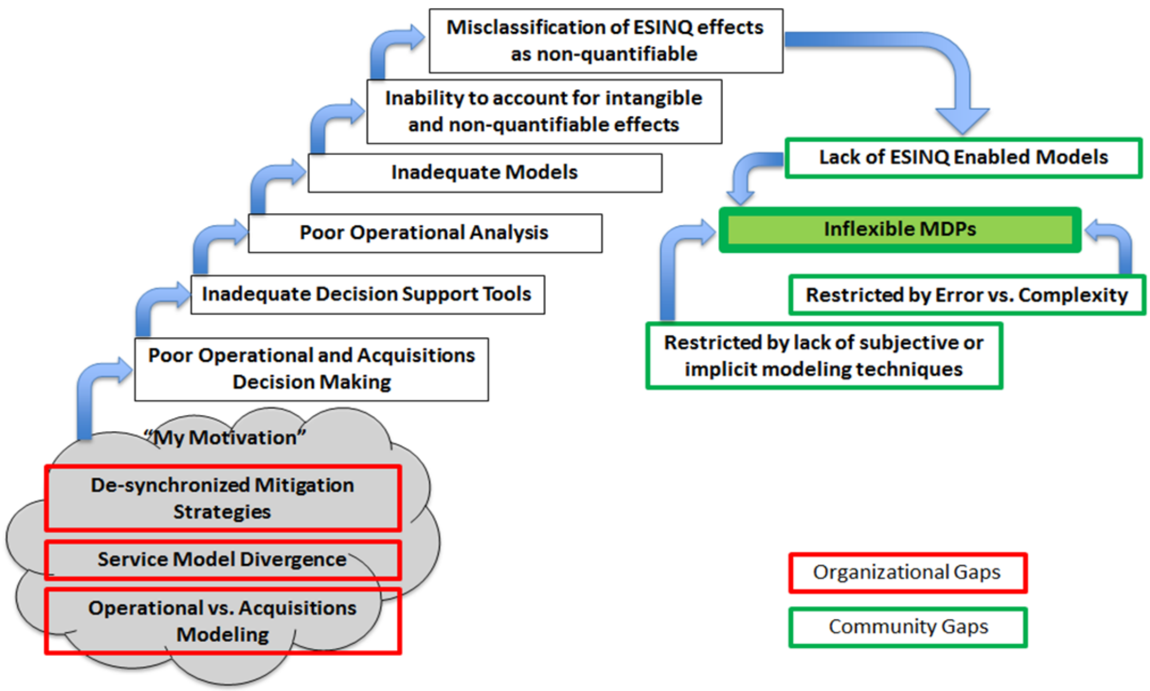


Figure 21. Gap Traceability: Organizational to Community

It is the author's belief that this chaos observed in U.S. military organization modeling stems in part from two sources. The first of these sources, and the focus of this work, are the gaps at the M&S community level, specifically with regard to the inflexibility of traditional MDPs to account for a more complete understanding of the OE in the development of the referent. By focusing on improving the underlying MDPs to account for ESINQ force multipliers during model development, it should be possible to produce better models, execute better OA, create better decision support tools, and thus, execute better and more informed decision making with regard to preparation for operations in a D3SOE. The second of the two sources, which was outside the scope of this work, is the belief that DOD senior leaders share some responsibility in enabling this failure. Models are developed based on requirements, and until a demand signal is sounded from the senior levels of the DOD to improve the capacity of combat models to address the gaps described in this work, only partial solutions will be possible. Unfortunately, with the threat growing faster than our capacity to mitigate, the United States is at a disadvantage and possibly unprepared to do what the AOC states it needs to "fight and win in a complex world." For this issue to be resolved we must look for new

and innovative solutions that address not just the threats, but the higher order interactions of the four referents of D3SOE mitigation, specifically at the M&S community level.

As described in Figure 20, there are gaps within current M&S practices that the author believes are hindering the ability of M&S practitioners to quantify the contributions and impacts from ESINQ effects on metrics of operational effectiveness. These gaps are further articulated by a 2010 JHU APL report which highlighted some significant gaps in M&S capabilities. These gaps included: what is modeled, referring to the aspects of the OE that are captured in the referent, and the ones that are ignored; limited modeling consensus, referring to the dissidence among M&S practitioners and the desynchronization of modeling across domains; M&S support to acquisitions, referring to the lack of any formalized process for using M&S in support of acquisitions; and the fact that “M&S developers lack understanding of modeling best practices, abstraction techniques, context dependencies, etc.” (JHU APL 2010, 1–2), referring to the inability of model developers to break away from the traditionally inflexible MDPs like those discussed in Section 2, and to embrace other modeling techniques that can better explore and capture the full context. These observations nest well with the gaps noted by Davis and Blumenthal in Figure 20, and help highlight the community level gaps that are currently limiting the ability of the U.S. military to prepare for operations in a D3SOE.

Community gaps are more generalized than the organization gaps discussed in the previous section, and are focused on addressing the six primary high level gaps within the M&S community, and include: the inability to model ESINQ effects; the limitations of traditional MDPs; the compromise between error and complexity; the failure to accept the value of subjective assessments; the lack of an implicit model development process; and the desynchronization between design space and solution space saturation. Each of these gaps will be discussed in depth over the next six sections, and will support a better understanding of the context of the problem faced when attempting to bridge the gap between current modeling practices and the desired end state of this work.

1. ESINQ Effects

To capture a more holistic understanding of the OE in the referent, one capable of evaluating the dependencies of systems on ESINQ effects, it "will require a fundamental shift from the current force paradigm based on expertise-centric missions and tasks, absent of tangible space-force capabilities" (U.S. Army 2014a, 13). To support this shift to a paradigm that captures tangible ESINQ effects, like space-based capabilities, a new methodology will need to be developed that can address the inability of current MDPs to account for the effects of external and context systems. By definition, external systems are those that are capable of impacting the system from across the boundary and can in return be affected by the system as well. Context systems on the other hand are defined as a "set of entities that can impact the system but cannot be impacted by the system" (Buede 2000, 50). Figure 22 shows the context diagram of an operational model, with double-headed arrows representing the interactions of the model with external systems and single-headed arrows representing the interactions of the model with context systems.

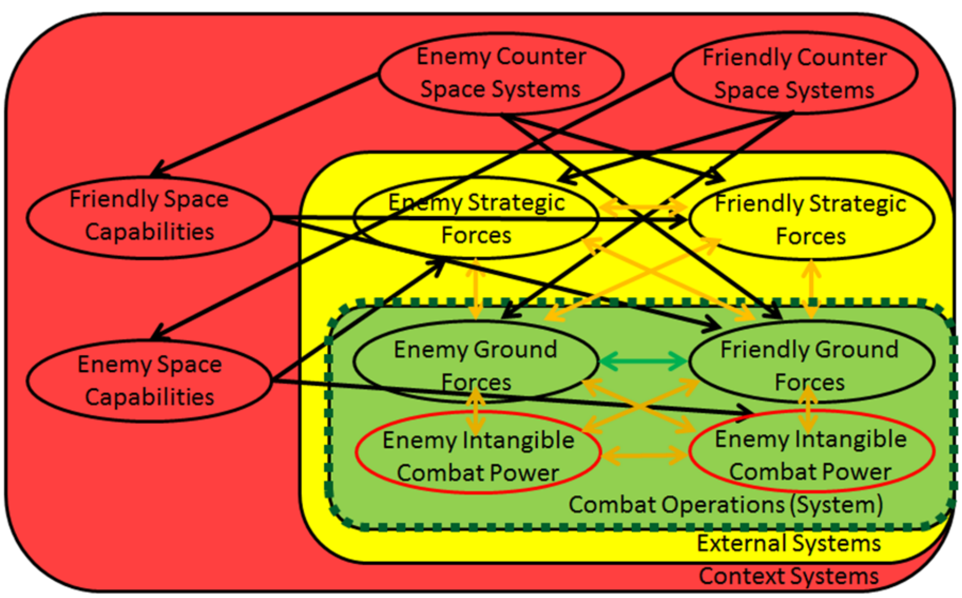


Figure 22. Modeling Context Diagram

As shown in Figure 22, the green area represents our system, which for this example is the combat model. The purpose of the model is to provide an accurate

representation of the aspects of the real world that are of interest to the modeler, which for this example may include the interactions of tanks, weapons, and artillery. Most agents in the system will be represented by hundreds of attributes that attempt to create a digital representation of the actual system within the model. While current models can account for the majority of the tangible interactions (green arrow) operating in the same domain, because of how the model was developed, they do not accurately account for intangible or non-quantifiable effects (orange/black arrows), especially across the domain boundaries. Thus, current models do not fully account for the complete OE in the development of the referent, even internal to the system boundary.

The yellow area represents the external systems, which with respect to the combat model, account for the impacts of higher echelon forces and systems on the combat model (orange arrows). In reality, this interaction would include the physical contributions to the model from all domains. However, in modeling these higher systems and effects are typically ignored, and the majority of their contributions to the model are either lost or aggregated within the modeled agents. This deficiency is primarily due to the fact that the contribution of many of these external systems to the current model can only be partially quantified, because many are behavioral impacts rather than physical impacts. For example, while the effects from higher echelon artillery and air strikes can be quantified in a combat model, effects from deep strike, strategic intelligence, BMC2, communications, logistics, and even political pressure are more difficult to capture because their observable impacts cannot be accounted for in physics based models. Thus, the ability to accurately model the OE is further reduced because current models cannot fully capture the OE of the external systems. The accuracy of the model is further reduced by the translation errors associated with modeling cross-domain effects in terms of the model's domain attributes. For example, consider modeling the impacts of cyber-attacks in terms of a ground combat model. To do so would be difficult because the attributes available within the combat model (a physics based entity model) are based on the ground domain, which typically do not include measures that can accurately define the effects of cyber operations, who's impacts do not directly affect the capabilities of the system. In reality, these effects would likely be observed as a combination of behavioral

effects, like slower decision making cycles by leaders leading to negative impacts within the model, as well as reduced SA, which would be observed as an increase in location/ targeting errors, also leading to negative impacts to the outcomes of the model. Yet, physics based models cannot adequately, if at all, address behaviors, which precludes applying such effects directly to the modeled systems, because in reality, their physics should remain unchanged. To overcome this issue, the impacts of these effects must be applied to the systems indirectly, and thus, a significant portion of the resolution needed to model cyber effects is lost due to the inflexibility of the ground combat model to account for systems outside the domain in which it was designed.

The red area described in Figure 22 represents the context system, which in the example of the combat model, represents the impacts of strategic forces like space and other ESINQ effects. As it is with external systems, this interaction is real, but the distinct difference is that the tangible contributions to the model from context systems cannot be measured, or more accurately, “is not measured.” Thus, context systems are often considered intangible and mostly ignored in models. While it is possible to incorporate context systems into the actual model, it would induce a significant amount of complexity, again due to the difficulty in translating behavioral impacts to observable impacts within physics based entity models. Thus, modeling efforts that attempt to capture some of the effects of external and context systems are only partially successful, as seen in Figure 22 (orange/black arrows), primarily due to three main issues. First, accuracy is lost in the representation of external and context systems and their tangible effects when integrated across the system boundary. Second, the model cannot account for seemingly intangible or non-quantifiable contributions, especially ones which primarily impact behaviors. Third, much is lost in translation when attempting to model cross-domain effects of external and context systems, which operate in domains other than the domain of the model and are often difficult to accurately represent in physics base models that typically lack the capability to model behavioral impacts.

These issues have created a situation in which model developers are unable to accurately account for ESINQ factors and effects, limiting them to just three methods to try to capture the effects of systems external the system boundary. In the first method,

developers can choose to ignore all interactions from outside of the system boundary. Depending on the intent and the purpose of the modeling effort, this may be a valid method for addressing certain objectives and goals, though careful consideration on the impacts from failing to account for the actual OE will need to be considered. While this seems like a faulty approach, it is common in the M&S community because it induces no increase in complexity, but it does fail to increase the accuracy of the model. In the second method, developers can add the functionality of the external forces and systems into the model by expanding the system boundary to encompass the external systems of interest across all domains. While the new expanded model would capture the tangible impacts of the external systems, as well as an increased representation of the OE, it would require a significant increase in complexity of the model, and require a substantial investment of resources to implement. Because of this complexity, this method is often limited to M&S developers with significant resources, like military and government agencies. In the third method, developers can select a specific external system or effect in which they are interested in, and insert these into the model as agents. While this would increase the model's capacity to account for the effects of these systems, it would do so through only a moderate increase in complexity due to the addition of agents and their associated attributes. Unfortunately, the ability of these agents to capture the actual effects of the systems which they aim to represent would be limited to just the tangible effects and level of resolution the model attributes allow. Simply put, models that attempt to represent systems from domains other than the ground domain, or systems that have seemingly intangible/non-quantifiable effects, or impacts to behaviors, will find it difficult to adequately represent their effects when they are limited to the agent attributes available in the physics based ground combat model. Yet, even with the inability to accurately address cross-domain systems, this is the method most model developers use.

Unfortunately, all three of these methods have significant disadvantages in terms of modeling. The first method ignores everything outside of the system boundary resulting in a less complex but less accurate model. The second method is far more accurate and captures a larger representation of the OE, but is considerably more complex and difficult to achieve, and can only partially represent these effects, especially impacts

to behaviors. And the third method is only marginally better than the first, gaining accuracy by capturing some of the tangible effects of external and context systems at the cost of increased complexity, but it fails to account for the seemingly intangible and non-quantifiable effects that impact behaviors. Luckily, this work supports a fourth option, an improved method for accounting for ESINQ effects.

While the effects of ESINQ systems like space and counter-space systems are hard to quantify, especially when these impacts can be classified as behavioral, we should be able to represent the effects they produce through the creative manipulation of surrogate factors. If we can capture just the significant effects of ESINQ systems on the entity model, to include impacts to behaviors, in a manner that can be translated to the model even after considering the significant aggregation and simplification of the effects due to the cross domain translation effects, we should be capable of providing a much better representation of the actual OE. Using this improved understanding of the OE, developers should be able to quantify and translate the effects of these ESINQ factors and effects into the operational model. While this IMDP would result in only a partial improvement of the model, it would for the first time address external, context, and ESINQ systems in a deliberate fashion, to include impacts to behaviors which are typically not addressed in modern physics based models. The model developers can then insert these effects into the model as modifications or adjustments to a few specifically identified agent attributes (surrogates) that already exist in the model. While these modifications would not increase model complexity, they would yield an increase in accuracy of the model by capturing effects across system boundaries and domains to include the tangible effects of the ESINQ effects that were previously ignored. While this method would require an upfront commitment of resources, such complexity would not be translated to the model. Thus, for models used frequently, the initial investment of resources would be more than justified.

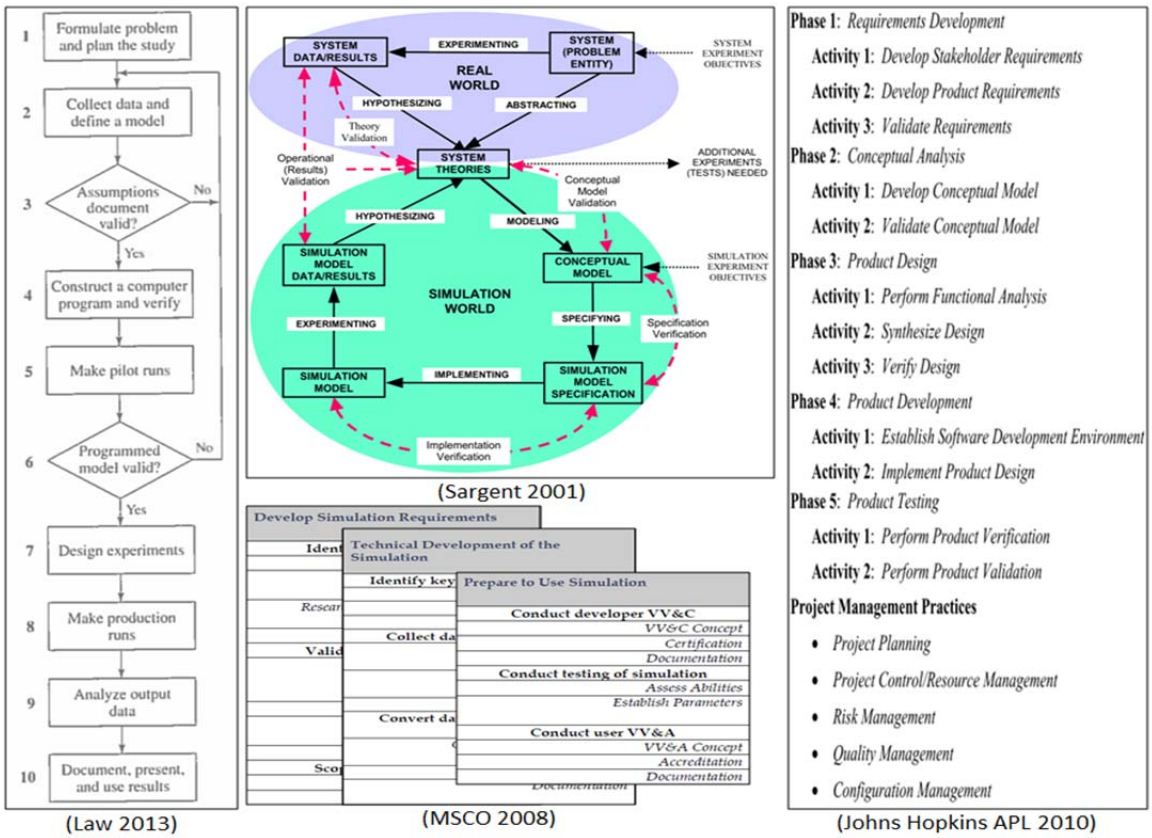
2. Traditional MDPs

While a plethora of MDPs are available for use, most of these MDPs provide only a simplified framework for executing model development. Couple these weakly defined

MDPs with the fact that most M&S users tend to distill these processes down even further, into an even more generalized framework which leads users through the definition, development, and analysis of a model. The issue with this is best captured in the following statement: “Although the importance and use of modeling and simulation (M&S) tools (models, simulations, and utilities) is expanding across the Department of Defense (DOD), relatively few persons have a good grasp of the process and principles that should be followed when developing such tools” (JHU APL 2010, ES-1). Thus, not only are traditional MDPs inflexible and poorly defined, but most users fail to even adhere to the overly simplified rules established in these MDPs. And while there are various schools of through within the M&S community regarding the importance of the model definition, specifically the development of the referent, Ilachinski (2004) for example, this work aligns with the more common of these schools of thought, that the referents establishes the foundational understanding necessary for the development of the model. To better understand the shortcomings of such traditional MDPs, let us begin by briefly discussing the history of MDPs, as well as exploring a few of the more prominent MDPs current in use within the community.

Models have been in use for 100s of years, likely longer, yet until recently these models were for the most part either conceptual or physical models (scaled analogs of something more complex that were often used as tools in support of gaining understanding). Following the advent of the computer, the definition of models was expanded in the 1960s to include computer-based models, which included the computer program as a legitimate medium for representing a model. With the technological advancements that computers facilitated, specifically in the rapid evolution of computing power, memory, and storage, computers drastically increased the capabilities of model developers to capture a larger and more accurate representation of the systems being modeled. With the rapidly expanding potential of computer-based models it became apparent that a more formalized process was needed to deal with the nearly exponential increase in model complexity. Enter the traditional MDP. Being rooted in the already existing systems development processes and functional models of the time, the MDP

sought to codify a more detailed process for developing computer-based models. Figure 23 shows what the author considers the four most commonly used traditional MDPs.



Adapted from DOD (2008a, 8–18), JHU APL (2010, ES-2), Law (2015, 67), Sargent (2001, 109).

Figure 23. Four Common Traditional MDPs.

Each of these four MPDs was developed to attempt to codify the process for developing computer-based models, yet each author did so with a specific focus and end-state in mind. Thus, there is significant variation among traditional MDPs, and to highlight the commonalities and differences, each MDP will be discussed in turn, starting with arguable the most widely accepted MDP, the one developed by Law (2013).

In his book, Law (2013) provides a basic, yet well-articulated MDP which he refers to as “steps in a sound simulation study” (66). While he devotes less than four pages to this topic, it is enough to support the development of a general model

development framework. Law does this by breaking his process down into 10 steps, three steps devoted to model definition, five steps devoted to model development, and two steps devoted to model analysis. He then provides a short general description of these steps, but with little detail regarding how they should be accomplished. Yet this is understandable, Law was attempting to provide a MDP that retained enough flexibility to be useful for most potential users, which required a more generalized process. When considering the nearly infinite uses for models, any MDP that was too specific would significantly reduce its potential usability. Yet, even after considering his reasoning, the MDP developed by Law seems to be lacking the detail necessary to conduct what he calls "a sound simulation study," specifically with regard to model definition.

The next MDP which will be discussed is the one developed by Sargent (2001), which he refers to as a "simplified version of the model development process" (107), which he later expands to include the application of model verification and validation as seen in Figure 23. Sargent breaks his process down into three steps, two steps devoted to model definition, and the third step devoted to model development, yet as with Law and Ilachinski, he does not provide any description or detail regarding how they should be accomplished. While Sargent does put more emphasis on the importance of the model definition step, his focus on producing a validated model overshadows the importance of the model definition step, specifically with regard to the development of an accurate referent. This highlights another issue with traditional MDPs, where the end state of many MDPs is seen in the development of a validated and accredited model rather than the development of the most accurate model possible.

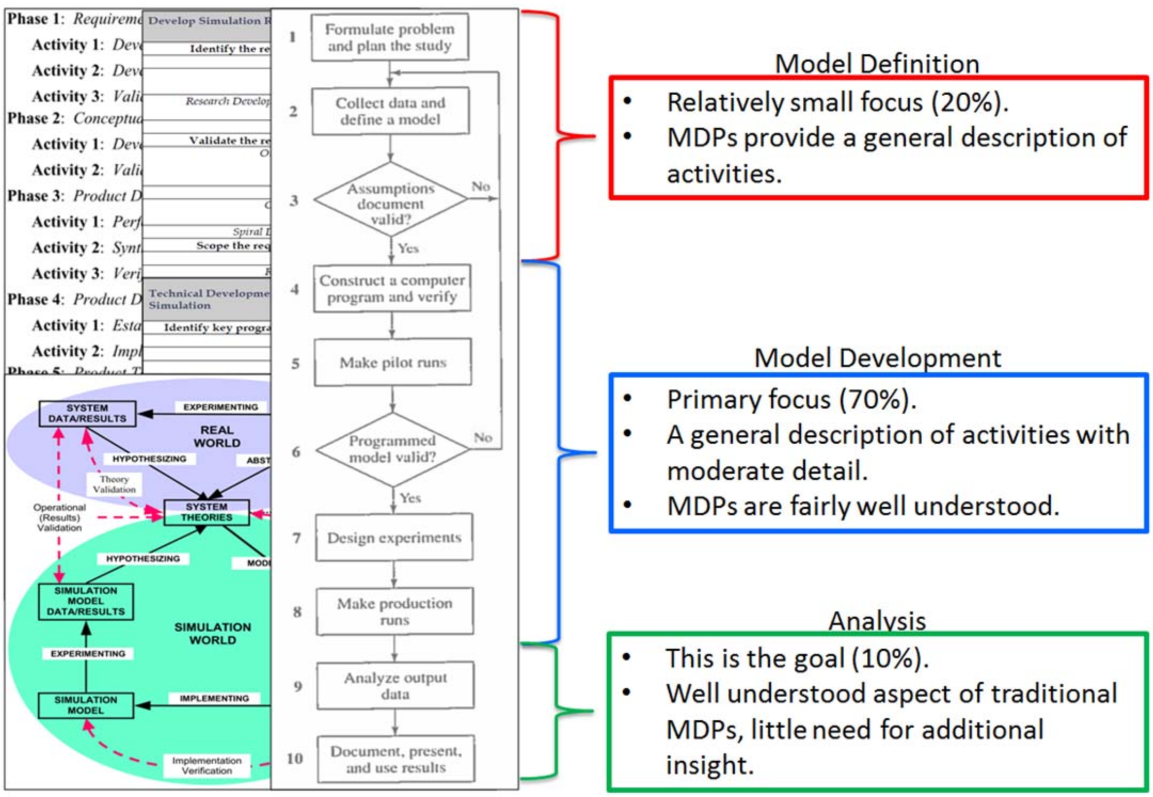
The third MDP which will be discussed is the one developed by the DOD in its Modeling and Simulation Body of Knowledge (2008). In this work, the Modeling and Simulation Coordination Office attempts to consolidate and standardize M&S knowledge for DOD users, and in doing so, codify a process of model development. While this work does a slightly better job at describing the steps of model development, it is done in a desynchronized manner, providing users with a loosely organized list of knowledge area concepts and associated descriptions, but with little-to-no traceability between the concepts or detail regarding how to execute them. Thus, users are forced to determine

which areas are pertinent to their work, how these areas should be executed, and then to link these concepts into a framework for implementation. While this approach may be useful in codifying a body of knowledge, it is not very useful as an executable process, failing to define the linear/iterative process necessary to develop models as well as the importance of establishing an accurate referent. Figure 23 highlights this issue, where the author was forced to cut and paste specific knowledge areas from throughout the lengthy document into a structure that resembles an executable MDP.

The last MDP which will be discussed is the one developed by JHU APL (2010). In this work, titled “Best Practices for the Development of Models and Simulations,” JHU APL took a unique approach to establishing its MDP, specifically through the distillation of existing SE practices, which were then each “assessed to identify its applicability to the M&S domain, along with its relative strengths and weaknesses. The results of these assessments were synthesized into a new SE Framework” (ES-1) for model development. JHU APL breaks his process down into five phases, not including the project management practices. Of these phases, two phases are devoted to model definition, and three phases are devoted to model development. As with Sargent, JHU APL puts more emphasis on the model definition step, which is very much in line with traditional SE practices, and thus, does a better job at capturing the importance of model definition than most other MDPs. Yet, differing from the other MDPs investigated, JHU APL put a significant amount of effort into codifying the details of their MDP, which can be found in their Best practices Definitions (JHU APL 2010, B-1-13). Additionally, and of significant impact to this work, JHU APL identified a general lack of detail in other processes as a significant gap within the M&S community, stating that:

> The most notable observation about this effort is that, although there have now been decades of focus on engineering processes and process improvement, much of it has been focused on systems and software in general, not on models and simulations specifically, and much of it at the macro level, rarely daring to drill down to the level of individual best practices. The study team was surprised by the lack of detailed best practices for the development of models and simulations in the literature. JHU APL (2010)

With a review of four of the more common MDPs currently in use, let us now explore these MDPs more generally by considering just the two general steps of most traditional MDPs, model definition and model development. Although analysis is typically the third step in most MDPs, it is not discussed here because its process is unaffected by the implementation of the IMDP. The generalized framework, overlaid with four examples of traditional MDPs can be seen in Figure 24.

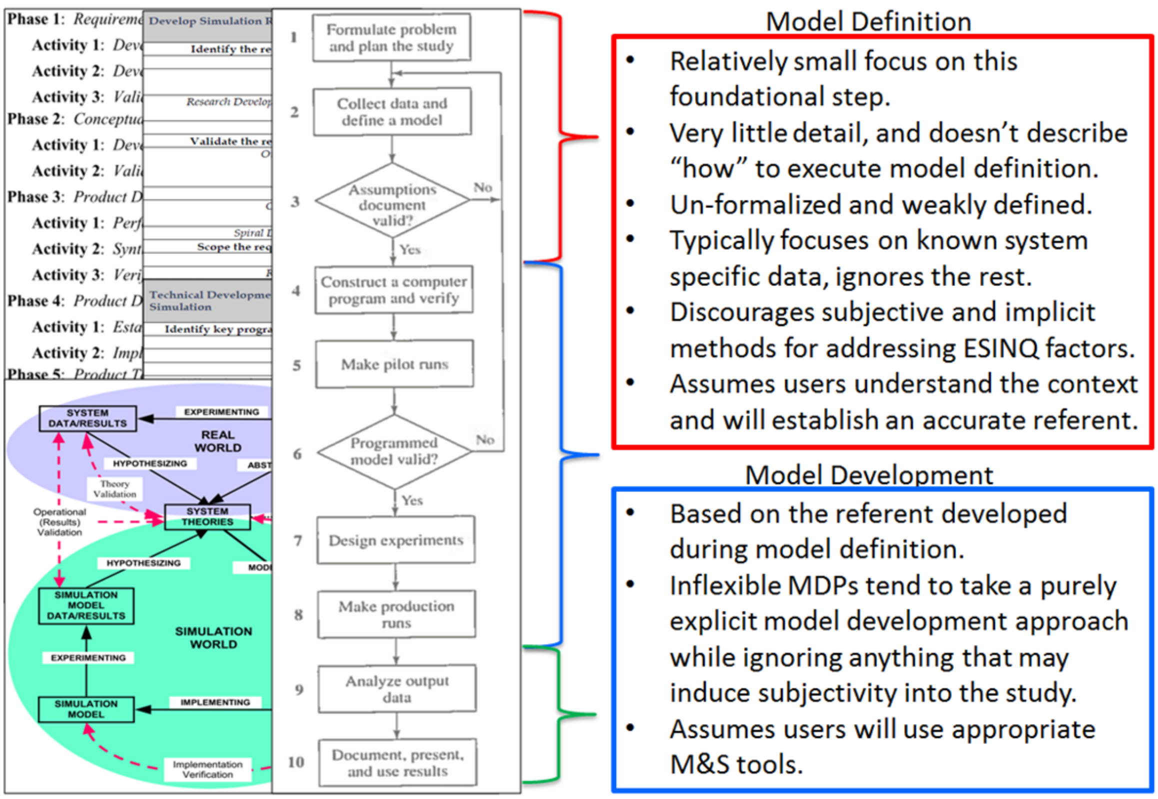


Adapted from DOD (2008a, 8–18), JHU APL (2010, ES-2), Law (2015, 67), Sargent (2001, 109).

Figure 24. Steps of a Traditional MDP.

Model definition includes the steps of identifying the problem, formulating a plan of action for the simulation study, and gathering all necessary information needed to inform model development, to include the development of the referent. Model development is concerned with the actual development of the model, to include test, evaluation, execution, and experimentation. This is the primary focus of most traditional

MDPs, and thus, receives the majority of the resources. Because of this focus, these steps are fairly well understood and articulated in modern writings. Most commercial M&S packages provide detailed model development processes, and almost all users of M&S are well versed in their own adaptation of these processes. Unfortunately, as described in Figure 25, there are some significant gaps with traditional MDPs.



Adapted from DOD (2008a, 8–18), JHU APL (2010, ES-2), Law (2015, 67), Sargent (2001, 109).

Figure 25. Gaps of a Traditional MDP.

As shown in Figure 25, most traditional MDPs underwhelm the model definition step, devoting a relatively small portion of the overall resource budget to this critical step, often assuming the user will ensure an adequate understanding of the OE is instantiated in the referent prior to model development. Thus, this step is for the most part un-formalized, weakly defined, and lacking any specific detail regarding how to conduct model definition, offering just a simple framework or best practices for users. This was

highlighted during the November 2015 dissertation defense of Sam Sok, who noted that with regard to MDPs, “All processes start by attempting to define the system. None of the processes explains how to define the system” (14). This lack of detail may result in users who hurry through this step and often limits the type of input data to quantifiable sources, which significantly limits the capacity of current MDPs to account for ESINQ effects. This incomplete understanding of the OE is then passed on to the model development step, which relies on the quality of the model definition step, which as described, is lacking in detail. The problem is further complicated by the fact that most traditional MDPs take a purely explicit model development approach, directing users to avoid hard-to-quantify input sources for fear of injecting subjectivity into the study. Thus, most traditional MDPs are ill-equipped to model systems or effects that can be considered ESINQ, resulting in the majority of ESINQ factors and effects being ignored.

The fundamental issue with the models produced using traditional MDPs is that the underlying assumptions and methods for gathering data during the model definition steps, specifically the development of the referent, are overly simplified. Thus, the models developed will fail to represent the OE and the systems they were intended to model, resulting in analysis based on an incomplete and more inaccurate model. The primary reason for the inability of traditional MDPs to capture an accurate assessment of the OE during model definition is their failure to recognize the existence of more than two sources of combat power in developing the referent. Figure 26 is a graphical representation of the author’s interpretation of the sources of combat power captured in the referents of traditional MDPs.

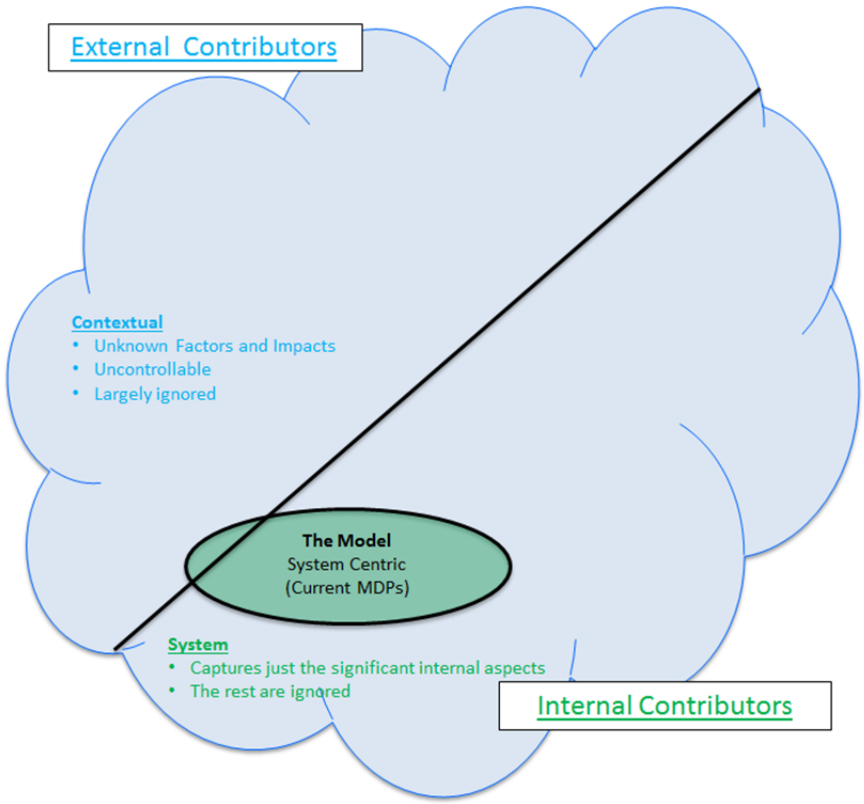


Figure 26. Traditional MDP Referent Contributors

As noted by MacCalman et al. (2016), traditional MDPs focus on just two contributors for the generation of the referent, where "the input parameters to the operational simulation are typically classified as one of two types" (2). These types include internal contributions, which capture key known system contributions, and external contributions, which bound unknown contextual contributions (typically distractors or degraders) of interest. The intent of the model (the green oval) is to capture enough key aspects of the system in the context of the physical world to provide an approximation of the system of interest, to include some of the interactions with the OE. Thus, the majority of the modeled combat power is derived internal to the system, with only minimal accounting of other contextual factors. Unfortunately, this approach ignores a sizeable portion of the actual contributions of both the system and the environment (the blue cloud), which can often contain a significant portion of the total combat power of the things being modeled. If the ignored sources are significant, then the models will underestimate a system's total contribution to operational effectiveness, an artifact that is

often seen in modern combat modeling. Of interest to this work is that the areas typically being ignored are often where external dependencies and ESINQ factors and effects reside. It is the belief of this author that there are more than two contributions that should be considered in the development of a model's referent. The first expansion of Figure 26 addresses the inability of traditional MDPs to recognize and account for the dependencies on external systems for the generation of internal combat power. This expanded view of modeling can be seen in Figure 27.

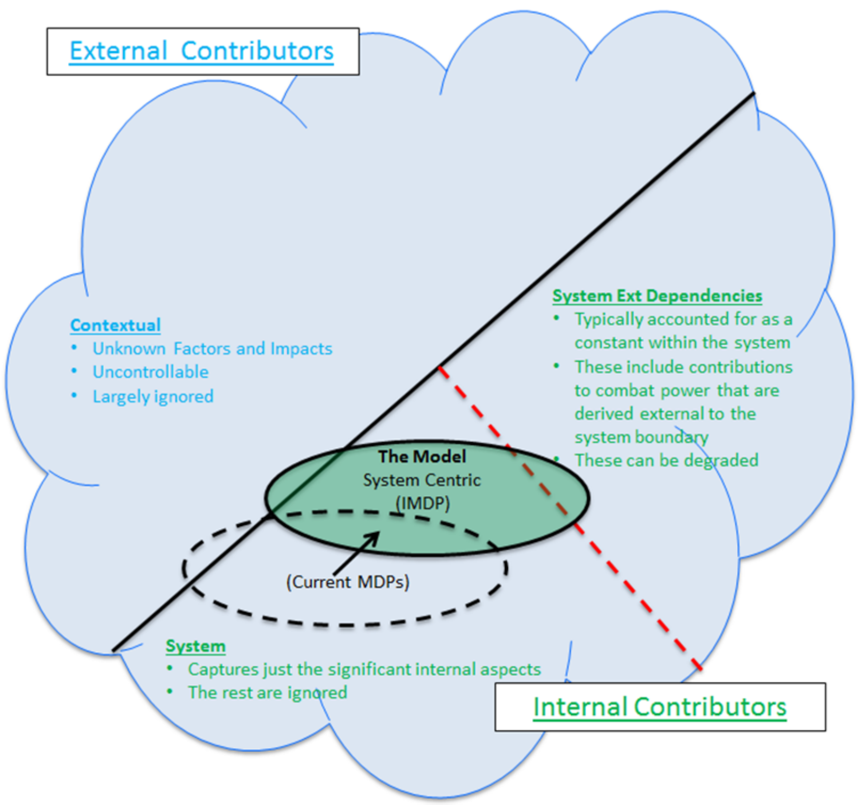


Figure 27. Expanded MDP Referent Contributors (External Dependencies)

As shown in Figure 27, by separating system internal sources of combat power into two areas—a system's internal contributions and a system's internal contributions that are externally dependent—it is now possible to decouple any dependencies the system has on external resources to generate internal combat power. Because most traditional MDPs either ignore these contributions or aggregate them with internal

contributions, most MDPs cannot account for the impact that external dependencies have on internal metrics of operational effectiveness. By expanding the sources of combat power from two to three, it is now possible to account for these sources separately, allowing us to capture a more accurate representation of the OE in the referent. In turn, users can degrade the portion of the system's combat power that is dependent on external support, which facilitates the quantification of the operational impacts due to a D3SOE, a key outcome of this work. The second expansion of Figure 26 addresses the inability of traditional MDPs to delineate between unknown and known external contributions to combat power. This expanded view of modeling can be seen in Figure 28.

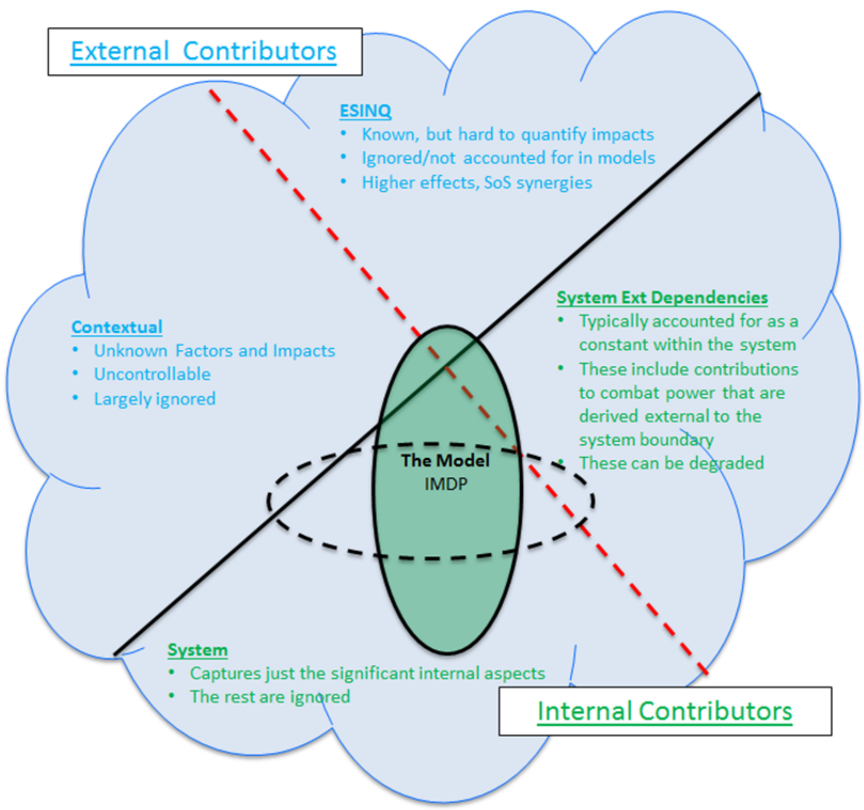


Figure 28. MDP Contributors Expanded for ESINQ Factors

By delineating between contextual factors and ESINQ factors, we highlight a fourth area of potential contributions of combat power that is currently unaccounted for within the referents of traditional MDPs. The key difference between the two is that

contextual factors are by definition unknown and/or uncontrollable, but ESINQ factors are not, they are both known and controllable, though they are often extremely difficult to quantify. By implementing an improved MDP capable of iterative implicit model development, it should be possible to expand the model to include all four of these potential sources of combat power within the referent and loosely quantify or “bound” the contributions from both externally dependent and ESINQ sources. While the majority of the modeled attributes are still derived internal to the system, the model can now account for all four potential sources of input, and thus, provides a more accurate depiction of the actual OE.

3. Error versus Complexity

A significant limiter to accurately representing the OE is the problem of complexity. In modeling, accuracy begets complexity, and complexity negates modeling. Simply speaking, there is a constant give and take between model accuracy and model error, and you cannot affect one without the other. This conflict was best described by Leinweber (1979) in his work “Models, Complexity, and Error,” as seen in Figure 29.

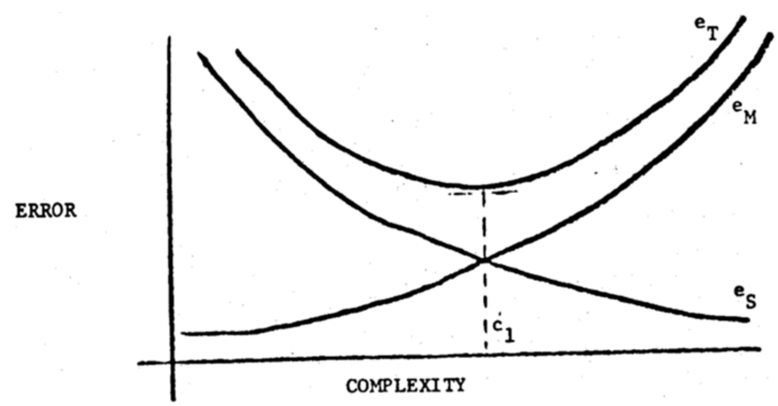


Figure 29. Error versus Complexity. Source Leinweber (1979, 11).

Error of Specification (e_s) decreases as you add more detail (complexity) to the model due to the inclusion of more information regarding the actual OE. Alternatively, Error of Measurement (e_m) increases as you add more information due to the compounding of inherent measurement error. Thus, there is a point of minimum error in

modeling that limits the amount of complexity a user would want to include. Any additional complexity added past this point would induce an increase in overall error and thus, may not be worth the effort. What is needed is a means to increase a model's complexity (accuracy at representing the actual OE) without the reciprocal increase in total error. One way this may be possible is through the creative use of implicit modeling. What if we could extend c_1 from Figure 29 to the right, allowing us to gain more accuracy before total error begins to increase? An example can be seen in Figure 30.

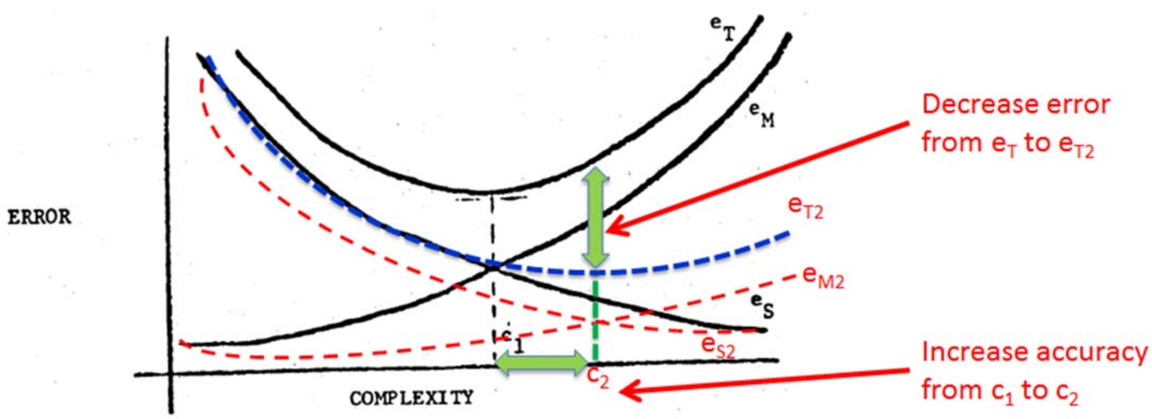


Figure 30. Error versus Complexity. Adapted from Leinweber (1979, 11).

By using implicit modeling techniques to capture the effects of ESINQ factors and effects on previously modeled attributes, it should be possible to increase model accuracy without increasing complexity, i.e., to reduce the slopes of both the e_s and e_m curves. Because the modeled agents can implicitly account for more than themselves, representing a larger portion of the OE, they induce less error of specification. Likewise, because the modifications of the surrogate factors within the models were calibrated, the error in measurement is also reduced. Thus, it allows for a more complex model before reaching the point of minimal error, which could be lower than the original.

4. The Value of Subjective Assessments

Another limitation of current MDPs is the common belief that subjective assessments are something to be minimized or avoided. This unfortunate trend within the M&S community has resulted in most MDPs pushing users toward more explicit studies

using primarily quantifiable data sources. While subjective assessments can indeed lack specific details, and do often rely on human assessments, they are not without merit. In fact, depending on the intent and implementation of the study, many subjective assessments can be extremely useful and provide analysts with unique and valuable insights that would have otherwise been ignored. Even if the study is somewhat subjective, if the study improves analysis and the decisions that result from that analysis, then it adds value. The benefit of coupling both explicit and implicit modeling techniques is best demonstrated by considering military decision making.

In the Army, generations of leaders have been matured with a firm understanding of the balance between the art and science of decision making. The science of decision making is typically backed with quantifiable facts and data, often sourced through intelligence and other trusted collection resources. Yet military leaders understand that there is a limit to what can be knowable and that for everything that is known, there is often more that is not. The art of decision making focuses on addressing these unknowns. It is by nature more subjective and relies heavily on the leader's own knowledge and experience, as well as assessments of his/her staff. Military leaders understand that they will not always have the best picture, but through a disciplined process like the MDMP, they can successfully plan and execute operations, even in the face of uncertainty. Good leaders are the ones that can merge both the art and science of decision making and use them to achieve better operational outcomes for their forces.

To achieve the balance between the explicit and implicit as seen in military decision making, the M&S community needs to avoid the rhetoric that labels subjective modeling as non-optimal. Unfortunately, even after Ilachinski (2004), a well-known figure in the M&S community, noted that, "a major ingredient of modeling and simulation consists more of art than science" (30), most practitioners of M&S still tend to avoid the art of modeling for fear of inducing subjectivity into the study. And while the source of this fear is rooted in modeling VV&A, VV&A in itself is no excuse for producing inaccurate models. Models that are based on inaccurate referents will likely pass VV&A assessments, but they are still inaccurate, and achieving the VV&A certification should not be the primary goal of any MDP, an accurate model should be.

The development of models focused on achieving VV&A certification is more of a programmatic risk mitigation technique designed to provide developer's protection and user's assurances than an M&S MDP. And while VV&A is valuable for specific cases, it has produced a community of model developers that have become more focused on achieving VV&A certification than producing the best possible models for the intent of their studies. Thus, the community finds itself in an environment which often neglects potentially insightful model development techniques like subjective and implicit modeling that could potentially improve the accuracy of models. By focusing on codifying a methodology for executing subjective modeling in a disciplined and scientific manner, the M&S community as a whole would be better equipped to handle a larger range of potential modeling requirements.

5. Implicit Modeling

Another creative way to attempt to capture the impacts of ESINQ effects in models is through implicit modeling. While not a new concept, because of the recent increase in acceptability of implicit modeling practices and its potential for addressing ESINQ factors and effects within models, it will be consider an emerging modeling effort in this work. Simply defined, implicit modeling is the representation of an unknown, qualitative, or ignored function that has been included or aggregated as part of a quantitative element in a model. Most model developers execute implicit modeling as a byproduct of more traditional MDPs, where the "details that are included are said to be *explicitly* represented and the excluded detail is *implicitly* represented" (Cares 2004, 2). Unfortunately, there is little thought to how these implicitly modeled effects are chosen, and even less verification of their significance to the outcomes of the model.

Unlike external effects, which can only represent known systems and quantifiable effects, implicit modeling could allow for the inclusion of all ESINQ factors and effects in models, whether known or unknown, quantifiable or not. In the past, implicit modeling has been heavily scrutinized because it fails to meet the first principles of modeling, specifically when considering the cause and effect so critical for model validation. But even under such scrutiny, the need for flexible modeling methodologies capable of

representing ESINQ factors has not gone unnoticed. When considering ESINQ effects and other soft factors, "first principles models are simply not adequate. For such phenomena, accurate prediction of outcomes, other than as aggregate probabilities, is simply a bridge too far" (Middleton 2010, 131). Thus, it may be time to start exploring the potential of models that do not uphold the first principles, and look at models that are more accommodating of the harder to quantify factors and effects like ESINQ effects. This need is best captured by a statement from the Navy: "there has been a chronic tendency for DOD modelers and analysts to avoid representing or considering 'soft factors' despite the fact that history tells us they are often dominant" (Committee on Technology for Future Naval Forces 1997, 26). For modelers who are interested in soft factors, as the author is with ESINQ effects, the subjective nature of assessing soft factors has forced the community to re-look at the potential utility of implicit modeling. It is obvious that first principle models are inadequate to address ESINQ effects, but does a model need to uphold the first principles for the insight generated for it to be useful? The author argues no, and that implicit modeling should not be dismissed outright.

In terms of this research, there are three key aspects that support the use of implicit modeling. First, is the fact that the ESINQ factors and effects of the most interest to this work are extremely difficult to represent in first principle models. The reason for this is the fact that the factors "we can measure easily do not capture critical intangibles: morale, leadership, unit cohesiveness and the like. Further complicating matters is the fact that generally, for a host of complex reasons, the whole is not just a simple sum of the parts" (Middleton and Mastroianni 2008, 4.2). Thus, the critical intangibles (ESINQ) of interest to this work do not lend themselves to traditional MDPs. Additionally, as noted by Middleton and Mastroianni (2008), traditional MDPs fail to account for the synergistic impacts that many intangibles have on the potential outcome of the model. This leads to the second reason implicit modeling shows potential, and that is the fact that implicit modeling has more flexibility to address the dependence of systems on ESINQ factors and effects for the generation of combat power. In traditional MDPs, this dependency would either be aggregated with the system in the model or ignored altogether, but with implicit modeling it should be possible to delineate the two, which

opens a host of opportunities with regard to model development, analysis, and applications. The third aspect that supports the use of implicit modeling is the fact that most ESINQ factors can be articulated in three ways. They can be modeled directly, or have their contributions to combat power linked to either SA or system attributes. Traditional MDPs can only model the known aspects of ESINQ factors directly in the model, ignoring the other two ways. An implicit MDP on the other hand can do all three: either directly as in traditional MDPs; by capturing the portion of the ESINQ factors that can be represented as system attributes, implicitly modeled as part of the system itself; or by capturing the SA piece implicitly through the use of surrogate factors in the model.

While implicit modeling techniques are often overlooked because of their questionable subjectivity, it is the author’s belief that with a logical and well thought out methodology, an implicit modeling technique has more than enough advantages for consideration as a legitimate MDP. And as noted by Middleton (2014), such a model could “still fall under the purview of scientific rigor, but there is a need to extend that concept to incorporate a ‘soft,’ incremental focus, where parametric analysis bounds regions of factor effects and the extent/significance of functional relationships, and where increasing levels of correlation correspond to increased acceptance of predictive validity” (7). By applying effort here, in the formalized definition of an implicit MDP, it should provide M&S users another tool set for addressing problems that do not fit well into traditional MDPs. As discussed by Middleton and Mastroianni (2008), for modern model developers to break out of the “to hard to do” traditional MDP paradigm, “closed systems modeling approaches need to be augmented with a new more flexible modeling paradigm” (5.5), one capable of accepting ESINQ factors and effects and supporting the development of models that can provide more robust insight into the OE.

6. DOE: Design Space versus Solution Space

Another potential gap with regard to modern modeling practices has to do with the potential misuse of DOE. While DOE provides significant utility to analysts, offering a detailed and efficient means for conducting model analysis, there are potential issues regarding the interaction between design space and solution space that must be

considered. While most DOE analysis practices achieve design saturation during DOE development, they can sometimes fail to ensure that the solution space is saturated as well. This failure can result in an analyst assuming that the DOE output, as well as the meta-models generated through that analysis, will accurately represent the system of interest. Unfortunately, this is not always the case and depending on the level of solution space saturation, can sometimes result in meta-models that are skewed. To highlight this potential issue, consider the DOE scatter plot in Figure 31.

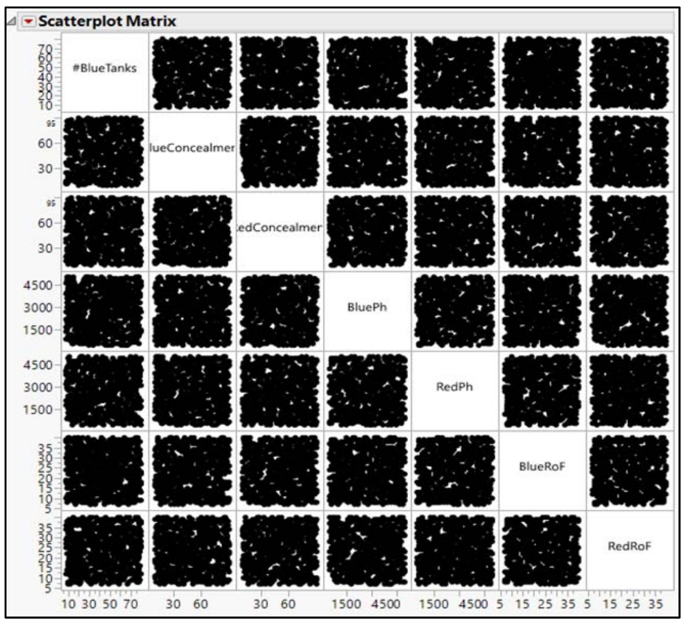


Figure 31. Design Space for a Seven Factor 2^{nd} Order NOLH

The design space of this seven factor 2^{nd} order Nearly Orthogonal Latin Hypercube (NOLH) design is highly saturated, ensuring that the interior space is being fully explored and is capable of identifying key interactions and dependencies of the factors. The 2^{nd} order NOLH was developed by MacCalman et al. (2017) and as he states in his work, has three key advantages which are key to this work: "First, they can fit the most commonly used polynomial metamodel with guaranteed minimal correlations; second, with suitable caution, they can fit higher-order models to a handful of factors; and third, they are space-filling allowing us to take full advantage of partition trees to find interesting behavior in local areas of the experimental region" (148). Thus, the 2^{nd}

order NOLH design allows for a more complete and thorough investigation of the solution space, while increasing the likelihood of identifying key system interactions. Following the execution of this design, analysis is conducted to draw out relevant insight. For this research, this process focused on establishing a baseline set of factor settings that would ensure that the model outcomes were calibrated to an expected victory curve across a range of potential Force Ratios (FRs). The analysis of the output from the design described in Figure 31 can be seen in Figure 32.

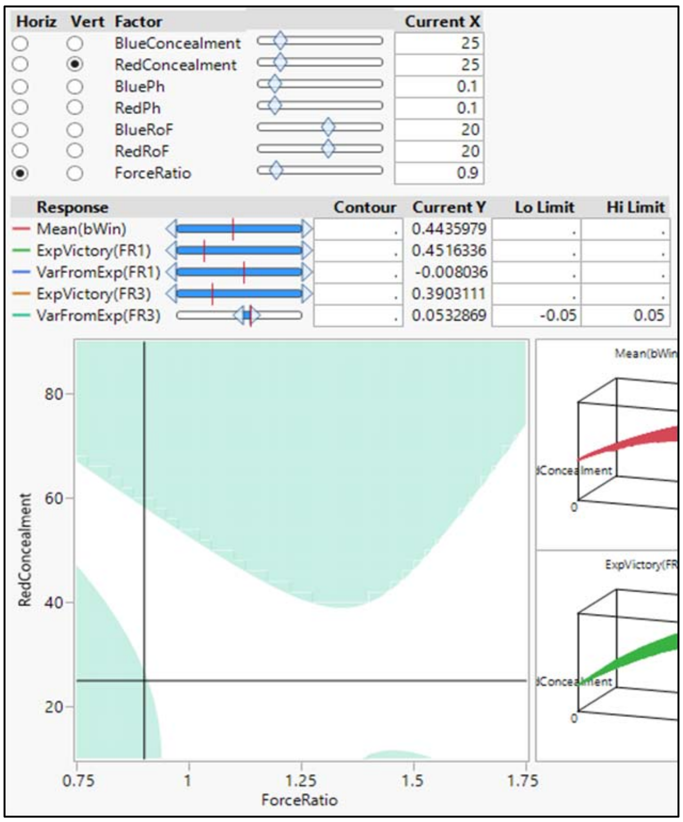


Figure 32. JMP Modeling of DOE Output Data

Based on the analysis conducted, the attribute settings shown at the top of Figure 32 should produce model outcomes that are within +/- 5% of the expected victory curve, across all FRs from 0.9 to 1.75. To verify, a one factor verification DOE was executed on the model with these agent attributes, where only the FR was varied. The plot of this verification can be seen in Figure 33.

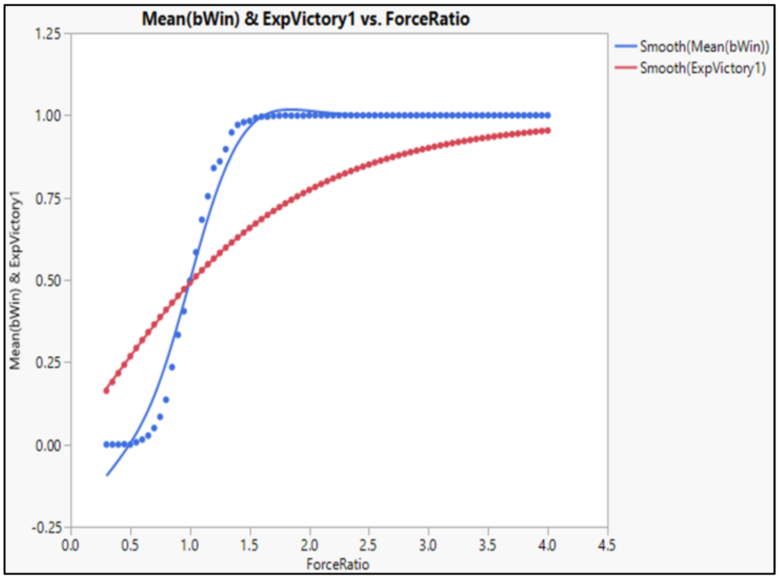


Figure 33. One Factor Verification DOE (Un-saturated)

As shown in Figure 33, the verification run produced a mean outcome curve (Blue) that was vastly different than the expected victory curve (Red) based on the analysis of the DOE output. Based on the analysis and agent attributes described in Figure 32, the model outcome curve should have been very similar (+/- 5%) to the expected victory curve, but this is not the case. In some instances, we see a variation from the mean of greater than 30%. This unexpected result highlights the issue with failing to ensure that the solution space is saturated. If a user of DOE fails to address the potential issues with regard to solution space saturation, it is possible for them to achieve skewed and inaccurate results as described in Figure 36, and they may not even know it. Figure 34 describes the output from the original DOE, which was used to produce the meta-models used by the JMP contour profiler shown in Figure 32.

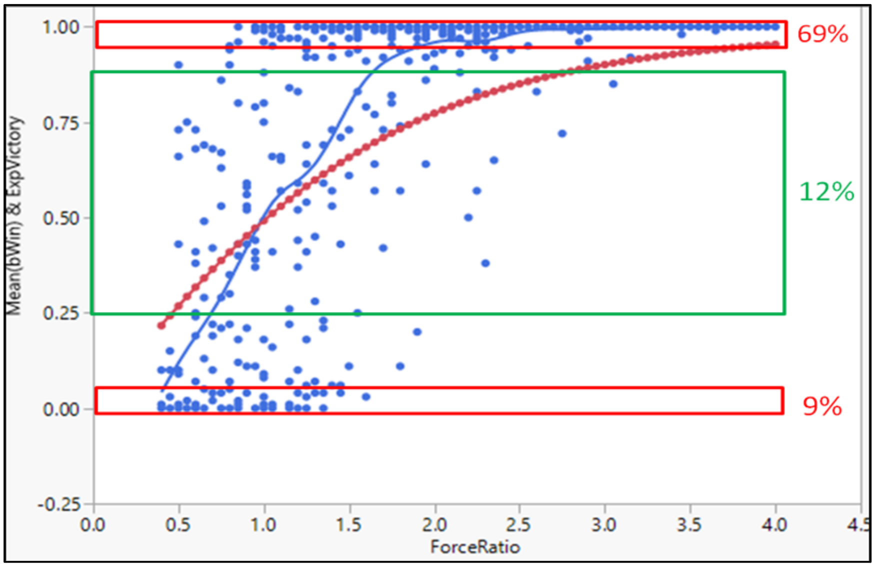


Figure 34. Un-Saturated Solution Space for a Seven Factor 2nd Order NOLH

Evidently, the design saturation shown in Figure 31 does not always ensure solution space saturation. In this example, only 12% of all Design Points (DPs) resulted in an outcome that fell within the range of interest. Thus, the analysis and meta-model development based on this un-saturated solution space produced skewed results that do not accurately represent the model, as we saw in Figure 33. An un-saturated solution space can be characterized by two general definitions. First, an un-saturated solution space will have less than 50% of the outcomes fall within the range of interest. Second, an un-saturated solution space will have an un-equal distribution of outcomes around the expected outcome curve, typically greater than a 10% deviation. Not only are the outcomes described in Figure 34 weighting heavily to the upper extreme, with 69% of the outcomes, but only 12% of the outcomes fall within the range of interest. Thus, using the author's definition of saturated, the outcome solution space is highly un-saturated, and the meta-models developed from the analysis of this data will likely result in skewed results that heavily favor the upper extreme as FR increases, which explains the shape of the model output described in Figure 33.

To avoid un-saturated solution spaces, users of DOE must take an iterative approach to DOE that focuses on reducing the dimensionality of the design. Through manipulation of the DOE ranges of each factor, the screening of factors for significance,

as well as increasing the design density through stacking, it is possible to increase the saturation of the solution space within the area of interest. A saturated solution space will support more accurate analysis, and once maximized, can produce much more accurate meta-models than achieved previously. Following DOE iteration and manipulation, Figure 35 describes a more saturated solution space.

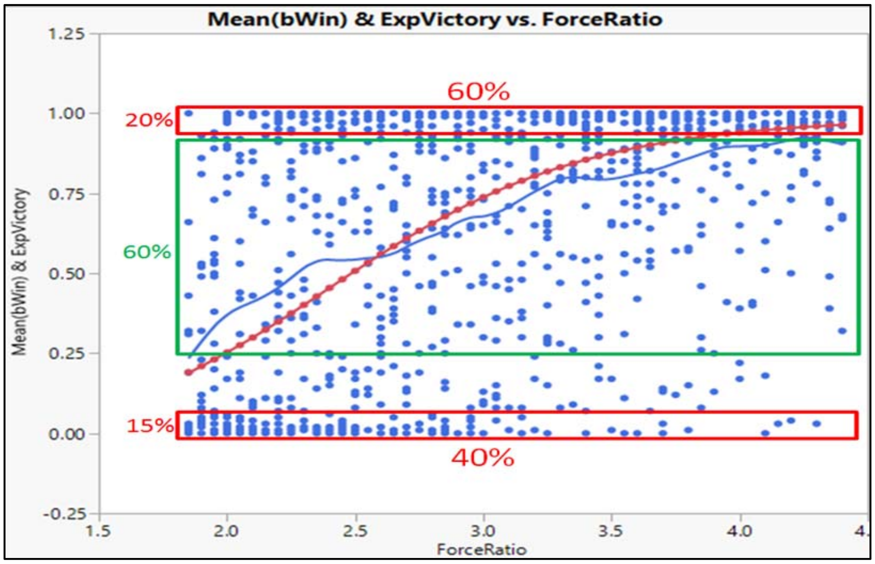


Figure 35. Saturated Solution Space for a Seven Factor 2nd Order NOLH

As depicted, the outcomes above and below the expected victory curve are relatively equally distributed, within 10% of the optimal 50/50 distribution. Additionally, at least 50% of the outcomes fall within the range of interest. Thus, the output described here is by definition saturated, and the analysis from this output should now produce meta-models that accurately represent the system of interest. To confirm, a one factor verification run was conducted, and the results of that analysis can be seen in Figure 36.

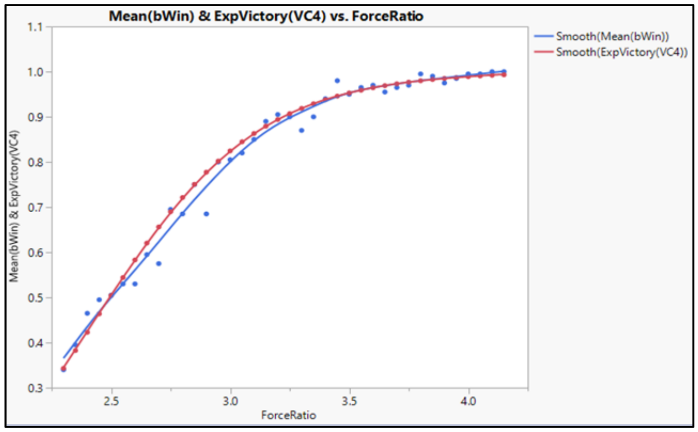


Figure 36. One Factor Verification DOE (Saturated)

Following the recognition of potential issues regarding solution space saturation, and the implementation of the recommendations laid out in this section, a more accurate meta-model can be achieved through an iterative process of DOE refinement that focuses on reducing design space dimensionality and increasing solution space saturation. Note that the model was not changed in any way, only the method in which the DOE was implemented. Thus, through a directed manipulation of the DOE, a meta-model was developed that was capable of better modeling the system it aims to represent.

D. SUMMARY

This chapter provided the reader with the foundational knowledge needed to understand the problem the U.S. military faces from operations in a D3SOE. It started by describing U.S. space dependencies, major adversaries and their counter-space capabilities, the new OE, and the associated vulnerabilities that the United States faces with respect to emerging threats. Next, it added a significant amount of detail regarding current and emerging mitigation strategies. The purpose of this was to provide the reader linkages between current and emerging threats and U.S. mitigation strategies, and to set the stage for identifying the potential gaps, specifically with regard to modeling. Finally, it addressed the modeling gaps which the author believes to be directly responsible for the inability of the United States to effectively prepare for operations in a D3SOE. This chapter highlighted the inability of current MDPs to capture the actual OE, as well as

addressed the underlying modeling issues, specifically discussing 1st and 2nd order gaps, domain segregation, error versus complexity, subjectivity, and the inability of current MDPs to quantify the impacts from ESINQ effects. It is this author's belief that through the development of an improved MDP that can address ESINQ effects, it will be possible to capture a more accurate representation of the OE in a model, and break the trend of developing 1st order systems, as shown in Figure 37.

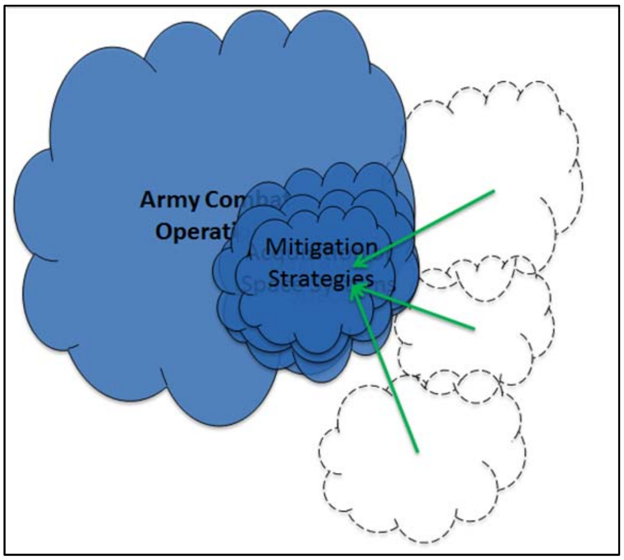


Figure 37. Methodology for the Development of 2nd Order Systems

By developing a methodology that can more accurately address ESINQ effects within a model, it will be possible to capture a more holistic understanding of the OE, and after sharing that understanding between the four referents, it should be possible to close the 1st and 2nd order gaps of D3SOE mitigation. By making operational and acquisitions decisions based on the performance of competing emerging space systems and strategies within this more complete understanding of the OE, we greatly increase the chances for success by producing a more robust system with direct traceability to metrics of operational effectiveness. Unfortunate, although the necessity for a better MDP has been recognized, the methodology needed to "build the bridge" from where we are (unprepared) to where we want to be (prepared) has not been codified.

III. AN IMPLICIT MODEL DEVELOPMENT PROCESS

The moral is to the physical as three to one.

—Napoleon (quoted in Moore 2017)

This research expands traditional MDPs by developing an IMDP that can more accurately address the modeling gaps described in Chapter II. The overarching goal of this work is to improve the decision-making process of leaders in both the operational and acquisitions communities by providing a more robust analysis methodology that can support the development of more accurate decision support tools. As stated in the 2009 National Intelligence Strategy, “being able to deliver capability cost-effectively when it is needed improves mission effectiveness, provides leadership with flexibility in making investments, and precludes gaps in necessary capabilities” (The Office of the Director of National Intelligence 2009, 16). The IMDP described in this chapter will provide analysts the means to simultaneously evaluate an emerging system’s performance across all four of the potential contributions to a models referent, and allow us to more thoroughly explore the four referents of D3SOE mitigation described in Chapter II. Because ESINQ factors are typically considered external to the system boundary and non-quantifiable, they have been largely ignored in the past. Yet ESINQ factors are very similar to Napoleons view of moral in the quote at the beginning of this chapter, and while they may be difficult to measure, can often have a significant impact on the outcomes of the model. The IMDP presented in this work will give users the ability to loosely quantify or “bound” the impacts from ESINQ factors on measures of operational effectiveness. The IMDP will facilitate a more complete understanding of a system’s performance with respect to the OE and thus, support the development of a range of new and improved operational and acquisitions decision support tools. These improved tools can be used to provide decision makers with a better representation of the OE by more accurately accounting for the impacts of not only the system, but of the ESINQ effects on the system as well. By following the IMDP presented here, a better representation of the OE can be achieved, which will allow for more informed operational and acquisition decisions

regarding the allocation of resources. Before we discuss the IMDP further, a brief review of MBSE and trade-space exploration methodologies is in order.

A. MBSE

MBSE is a relatively new concept within the SE community best covered in the works of Wymore (1993), Friedenthal, Moore, Steiner (2013, 2015), and Law (2014). The International Council on Systems Engineering (INCOSE) defines MBSE as the "formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (International Council on Systems Engineering 2007, 15). MBSE differs from traditional SE in that it takes a more upfront and formal approach to the use of modeling in the SE process. In fact, the only difference between the INCOSE MBSE and SE definitions is that MBSE highlights the "formalized application of modeling" in support of the SE process. Yet the significance of this slight variation is profound. MBSE attempts to replace many of the older "documents based" processes common within the SE communities with a more "model-centric" approach to SE. As technology has advanced, so has the accuracy and complexity of most systems architecture software packages, which have begun to surpass the capacity of most document based SE processes to maintain an accurate and complete record of the system. To address this shortfall, models are taking a more essential role in modern day SE practices, replacing the analog tools of the past that can no longer keep pace. Figure 38 shows a simple graphical representation of the linkages between MBSE, TSE, and M&S.

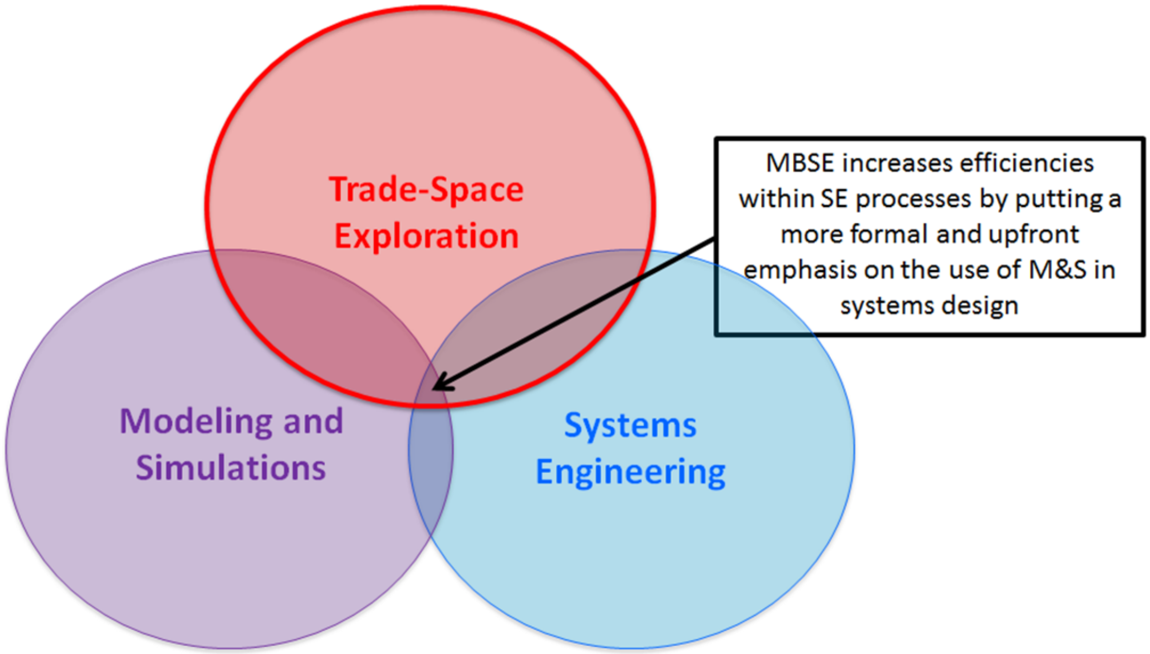


Figure 38. SE Analysis Methodology

From the author’s perspective, MBSE uses M&S and TSE techniques to better inform the SE process, attempting to expand the overlap of M&S and TSE within the SE community. The overarching goal of MBSE is to improve the efficiency of the SE process through better integration of modeling earlier and throughout the systems life cycle. The major benefits of employing MBSE as opposed to traditional SE are highlighted in the work of (Friedenthal, Moore, and Steiner 2015, 20), which describes the six primary benefits of MBSE. These include enhanced communications, reduced development risk, improved quality, increased productivity, the leveraging the models across the system life cycle, and enhanced knowledge transfer. Thus, it is easy to see the advantages that MBSE can bring to system development programs. A major theme in modern acquisitions, especially in the DOD, is the need to develop more efficient processes that reduce risk and cost while delivering more capable systems through the use of “streamlined processes to improve readiness and speed acquisition” (U.S. Army 2014b, 20). Of the six primary benefits of MBSE, three deserve additional consideration.

The first benefit of MBSE to acquisition programs is reduced developmental risk. By framing a more complete understanding of the system with respect to its OE, program

managers are able to better estimate system programmatics during the conceptual design phase and thus, reduce the risk of cost and schedule overruns, which are all too common in modern acquisition programs. The second benefit is improved quality. By implementing the MBSE process, organizations should be able to produce more capable and resilient systems that better meet the requirements of the stakeholders across a wider range of OEs. Because the MBSE process emphasizes a more upfront investment of M&S than traditional SE processes, especially during the concept development phase, MBSE provides greater traceability of system requirements across all phases of the SE process, ensuring a more complete and unambiguous understanding of the system. The third benefit of MBSE is increased productivity. Because MBSE supports the building of a more accurate understanding of the system and its requirements earlier in the system life cycle, the need for iterative design is significantly reduced, yielding a more timely SE process. Additionally, by more fully exploring the system trade-space and conducting system effectiveness analysis earlier in the system life cycle, the chances of producing a more capable system are increased. Thus, the development of a better understanding of the interactions of the system with the OE during the conceptual design phase as well as the potential trade-offs among the system alternatives is critical. And as noted by MacCalman et al. (2015), by focusing on a data driven approach to design like MBSE, "the end result will be better informed decisions, faster engineering, less rework, and allow for a wider range of alternative solutions" (5).

In addition to the benefits that MBSE brings modern acquisitions programs, there is a relatively new concept in current MBSE analysis methodologies that is of considerable interest to this work, and that is the concept of OEM. Traditionally, the SE process attempts to achieve stakeholder needs by developing an appropriate design through system tradeoffs of MOPs and iteration, and then by measuring that design against MOEs in the appropriate OEs. Unfortunately, even after creating numerous system designs during alternative generation, there is no way to ensure that the most robust designs will be captured. Loosely defined, a robust design refers to a solution that provides a more stable outcome across a wider range of potential environments. An optimal design on the other hand provides the best possible outcome under a very specific

set of circumstances. Unfortunately, this specific set of circumstances typically only accounts for a small portion of the actual OE in which the system will likely perform. Thus, robust designs are often more desirable in modern SE practices where a great deal of uncertainty resides, and while they typically do not perform as well as an optimal system, they do so more stably across a much larger range of potential environments than optimal systems. The inability of traditional SE methodologies to capture the most robust designs is due to two major reasons. First, MOPs rather than MOEs tend to drive system design choices, which are highly biased due to the dependency on human expertise. Second, traditional SE approaches cannot generate a sufficient number of design alternatives to ensure the solution space is saturated. In his work, Brown (2013) highlights that "an early structured search of the design space through the synthesis and assessment of hundreds or thousands of alternative concepts is essential for sufficient understanding of the relationship among cost, effectiveness, and risk" (10). To address this shortfall, some emerging TSE techniques and MBSE analysis methodologies have surfaced that use OEM to take the reverse approach, using MOEs to drive design decisions by establishing traceability between a systems design characteristics and its operational effectiveness. Thus, a more thorough exploration of potential design alternatives can be made, which is much more likely to capture a more robust system design and produce a more capable system.

B. TRADE-SPACE EXPLORATION

The purpose of this section is to provide the reader with a brief introduction to some of the recent advancements in SE analysis methodologies that have shown potential for improving the capabilities of SE and MBSE process to support better TSE. Specifically, this section discusses the work of Dr. Alex MacCalman (2013) and his efforts in developing a state-of-the-art 2^{nd} order DOE tool that allows for a more complete exploration of a system's trade-space by more accurately accounting for the higher-order interactions of a system. While most SE processes execute TSE at some level to support better decision making, these process are often constrained by complexity, limiting the breadth and depth of the analysis of the solution space to just a few alternative designs. While the work conducted by Dr. MacCalman focused on the

creation of a genetic algorithm, followed by the creation of the DOE design tool that used this algorithm to produce new designs, the aspect of his work that most interested the author was how these improved designs could be used to enable a more thorough exploration of the trade-space. MacCalman et al. (2016) highlight how advanced DOE can be used to execute TSE more effectively, enabling engineers to "simultaneously explore the operational and physical domains using statistical surrogate models in order to illuminate trade decisions between the system's operational effectiveness and physical design considerations" (1). By synchronizing both operational and synthesis models through the use of meta-models that captured a more accurate understanding of the OE, it was possible to more accurately link a system's functions to physical components. This improved understanding allowed for a more complete visualization of the trade-space and allowed users to observe the impacts to system performance based on changes to the functional and physical architectures. It is this improvement that is at the heart of the author's interest in his work. His efforts expanded the use of TSE to more accurately link M&S and MBSE, and as seen in Figure 39, enabled a more accurate representation of the OE during system design.

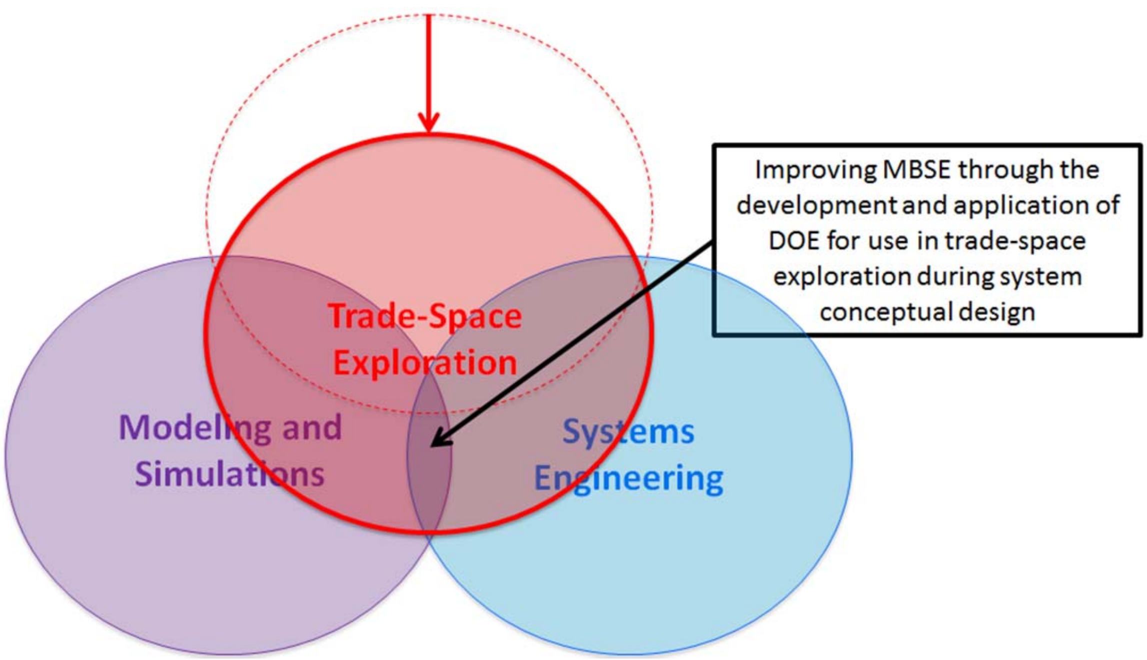


Figure 39. MacCalman's Expansion of SE Analysis Methodologies

As shown in Figure 39, the use of advanced M&S techniques, including DOE, can support a more complete and accurate TSE during the MBSE process. By improving the quality and density of the data feeding MBSE analysis, a more accurate representation of the system's interactions with the OE can be characterized, highlighted by an increased overlap and yielding a more insightful TSE than previously possible. Yet, even with the ability to more accurately capture the OE through the use of advanced DOE, MBSE analysis methodologies still lacked a formalized process to implement TSE in conjunction with system architecture steps and products, specifically with the integration of these synchronized products into external models.

C. MBSE ANALYSIS METHODOLOGIES

The purpose of this section is to provide the reader with a brief introduction to MBSE Analysis Methodologies, specifically the MBSE MEASA developed by Beery, which expanded upon the work of MacCalman. In his Dissertation, Beery describes various shortcomings of the then current SE and MBSE analysis methodologies which could limit a system engineer's ability to fully describe a system. These gaps have been binned into four overarching shortcomings: unsynchronized SE architectures, limited linkages between Systems Modeling Language (SysML) products and M&S, the inability of current analysis methodologies to support TSE, and the lack of SE architecture linkages to operational effectiveness. The intent of the MBSE MEASA was to address these shortcomings and support a better understanding of the system through the "analysis of models and simulations that consider not only system design attributes (as is done in each of the MBSE methodologies presented in the previous chapter) but also environmental and operational factors during system conceptual design" (Beery 2016, 66). The MBSE MEASA formally defines the process for ensuring synchronization between the functional and physical architecture processes and the development of SysML products for integration into the external models which will be used to access system performance, all while maintaining traceability to stakeholder requirements. By doing so, the MBSE MEASA successfully "establishes the formal linkage between operational need and physical system configuration that should be the focus of any MBSE based analysis methodology" (Beery 2016, 71). Like all MBSE analysis

methodologies, the MBSE MEASA captures all the key SE process necessary to fully describe a system, but more importantly, the MBSE MEASA provides a means in which to translate those physical and functional descriptions to the external model, which had not previously been codified. Beery was able to demonstrate the utility of his contribution by applying a set of SysML products of an emerging mine warfare system to the development of an improved mine warfare model. Then, through the use of advanced DOE and TSE techniques demonstrated by MacCalman, use the model to generate detailed data to support robust analysis needed to investigate the effectiveness of the emerging system compared to the legacy systems. For more detail regarding the MBSE MEASA please refer to (Beery 2016). Figure 40 shows a simple diagram of how Beery's work expanded the capacity of MBSE to support SE and TSE.

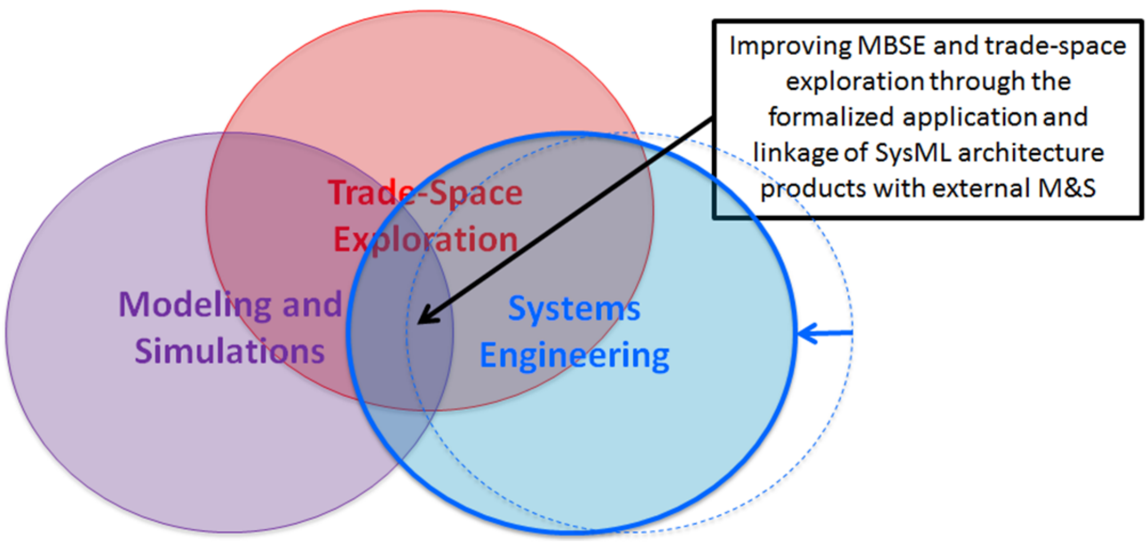


Figure 40. Beery's Expansion of SE Analysis Methodologies

Beery's work allows for an expanded integration between MBSE and M&S to support better TSE, denoted by the increased area of overlap. By formalizing the process in which architecture products can be synchronized for integration into external models, a more accurate representation of the systems interactions with the OE can be characterized in MDPs. Thus, as before, the overall understanding of the system and its interactions are improved, yielding more insightful TSE than previously possible. It is because of this

improved capacity to capture a more accurate understanding of the system, the translation of that understanding to operational and synthesis models, as well as its robustness for exploration of the system trade-space through OEM, that it was selected for use as the basis for the acquisitions support tool which will be described in Chapter V. With that said, there remains some significant shortcomings in current TSE and MBSE analysis methodologies, specifically with regard to MDPs, that limits the usability and effectiveness of current methodologies to consider the impacts of ESINQ factors.

D. AN IMPLICIT MDP

This research addresses what the author believes to be a few critical shortcomings of current M&S practices and techniques that have significantly limited the effectiveness of M&S to support modern TSE. The goal of the IMDP is to address these shortcomings by capturing a more accurate representation of the OE (the portion of the real world that comprises the context for the model) and its impacts on system performance. By doing so, the IMDP should be capable of better accounting for the model development gaps identified in Chapter II and result in a more complete understanding of a system and its interactions with the OE during the SE process. However, before the IMDP is defined in detail, a brief re-cap of the shortcomings of current MDPs and MBSE analysis methodologies is in order.

1. Background

While modern MBSE analysis methodologies provide a robust methodology for building a better understanding of the system and its interactions through the synchronization of systems architecture products with M&S, it fails to address the effects that ESINQ factors have on system metrics of operational effectiveness. This failure results in an exploration of the system trade-space based on an incomplete understanding of the OE. Thus, by developing a methodology that supports the inclusion of ESINQ factors within the model, current MDPs will be improved. During the investigation of traditional MDPs in this work, two primary gaps and one secondary gap were identified that the author believes could be addressed through the expansion of the current MDPs and MBSE analysis methodologies to capture a more accurate understanding of the

system and its interactions with the OE. The primary gaps were based on the authors own observations of the state-of-the-art, and focused primarily on the bounding of ESINQ effects within the MDP, as well as the creation of a formalized methodology for identification and selection of appropriate M&S packages, the MSSSM. Because the MSSSM is more generalized than the implicit modeling of ESINQ factors that is of primary focus, it is outside of the scope of this work, and its development will not be discussed in any detail here. For more detail regarding the MSSSM, please refer to Chapter I and Appendix A. The secondary gap was based on the future work section of Dr. Beery's dissertation as well as the author's desire to support the acquisitions of emerging space systems. Here, the focus was on the expansion of current MDPs and MBSE analysis methodologies to address the modeling of non-traditional systems, which ties directly to a contribution of this work, which was to use M&S to explore the capacity of emerging systems to mitigate the operational impacts from operations in a D3SOE. Let us briefly discuss both of these gaps, starting with the bounding of ESINQ effects.

While current MDPs and MBSE analysis methodologies support the development of more accurate system definitions, neither can adequately address ESINQ factors and their impacts on the system. In an age when network-centric operations of highly technical systems has become the standard, little has been done to fully understand or capture the dependencies that modern systems have on ESINQ factors to generate internal metrics of system effectiveness. Simply put, as modern systems continue to evolve increased dependencies on external elements, our understanding of those systems will continue to diverge from the ground truth because we cannot accurately attribute or quantify the impacts of those external elements. The issue with this divergence is similar to the issues revolving around the inability of most combat models to account for soft factors like moral and leadership. This failure is best captured by a statement from the Navy which stated that "this disjunction between model and reality has long undercut the credibility of most combat models with warriors, historians, and analysts willing to recognize soft factors and uncertainty" (Committee on Technology for Future Naval Forces 1997, 26). The inability to account for soft factors, which are included in the definition of ESINQ, has created an environment where modern models routinely ignore

potentially significant contributions to a systems' total operational effectiveness. This produces models that can often underestimate the operational effectiveness of the systems being modeled, and can be linked to two primary causes. First, when external sources that contribute to a systems internal operational effectiveness (MOPs) are ignored, leaving part of its total contribution unaccounted for in the overall system assessment. Second, when the external sources that contribute to the systems overall external operational effectiveness (MOEs) are ignored. Thus, the models developed using modern MDPs are inherently inaccurate. And though George Box famously said as far back as 1976 that "All models are wrong," the point here is that current MDPs produce models that are "more wrong" than they could/should be. By ignoring some potentially significant modeling input sources, traditional MDPs fail to capture a more accurate representation of the OE. As noted by the Committee on Technology for Future Naval Forces (1997), this divergence from reality has undermined the credibility of most models with users. These flaws derive from the failure of the model to capture the contributions of ESINQ factors on measures of system effectiveness, as measured both inside (MOPs) and outside (MOEs) of the system boundary. Unfortunately, as the dependencies of modern systems on external support continue to rise, so will the inaccuracies of traditional models. Now, let us discuss the secondary gap that the author believes could be addressed through the expansion of the current MBSE analysis methodologies and MDPs, specifically, the modeling of non-traditional systems.

Potential systems current under investigation for mitigating operational risks from adversary use of counter-space capabilities lies in the development of emerging space capabilities like SmallSats and HAAS. These systems are conceptually complex, being designed to operate based on multiple operational concepts, with sometimes contradicting missions. Thus, the assessment of these systems and their capability to mitigate operational risk is difficult to quantify because not only are there sometimes differing requirement, but most models are unable to account for the majority of the external dependencies of a system as well. From one perspective, the system is assessed from a traditional SE approach; where the system's capacity to execute system level functions is weighed again internal system level MOPs and external MOEs. Yet on another hand, the

secondary roles of the system is assessed from a non-traditional approach, where the system’s capacity to effect the overarching organizational structure, the System of Systems (SoS), is the primary metric for measuring internal SoS MOPs and external SoS MOEs. Thus, the increased complexity of the external interactions and dependencies of these systems as well as the variable means for which the system is assessed leads to their classification as non-traditional systems. Non-traditional systems can be loosely defined as systems that cannot be easily modeled or assessed using common and widely accepted M&S and SE processes. As stated by Beery (2016), “the most direct contribution consists of expansions and redefinitions of the MBSE MEASA to non-traditional systems (systems with limited control over design as well as systems that exhibit emergent behavior are potential examples, although others may exist)” (186). Non-traditional systems require a different approach to design than traditional systems because their capabilities are often not measured at the system level; rather, they are often measured at both the system and SoS levels. Simply stated, the primary MOEs of these non-traditional systems define how well they perform their mission in the context of the system, as well as how well they support the MOEs of the larger SoS. Thus, the assessment of the systems effectiveness is difficult to model because of the differing and sometimes competing requirements between the system and SoS. An expanded MDP and MBSE analysis methodology that can account for the dependencies of a system on ESINQ factors could help define a better understanding of the linkages and dependencies of non-traditional systems on the external environment and the SoS.

Now that the major shortcomings of current MDPs and MBSE analysis methodologies have been discussed, it is appropriate to discuss where these shortcomings can be addressed. To highlight these shortcomings, consider the generalized MDPs described in Chapter II. Simply speaking, the majority of the gaps and shortcomings of modern models reside in the MDP, specifically, the model definition step. As shown in Figure 41, the IMDP addresses these shortcomings in three major ways.

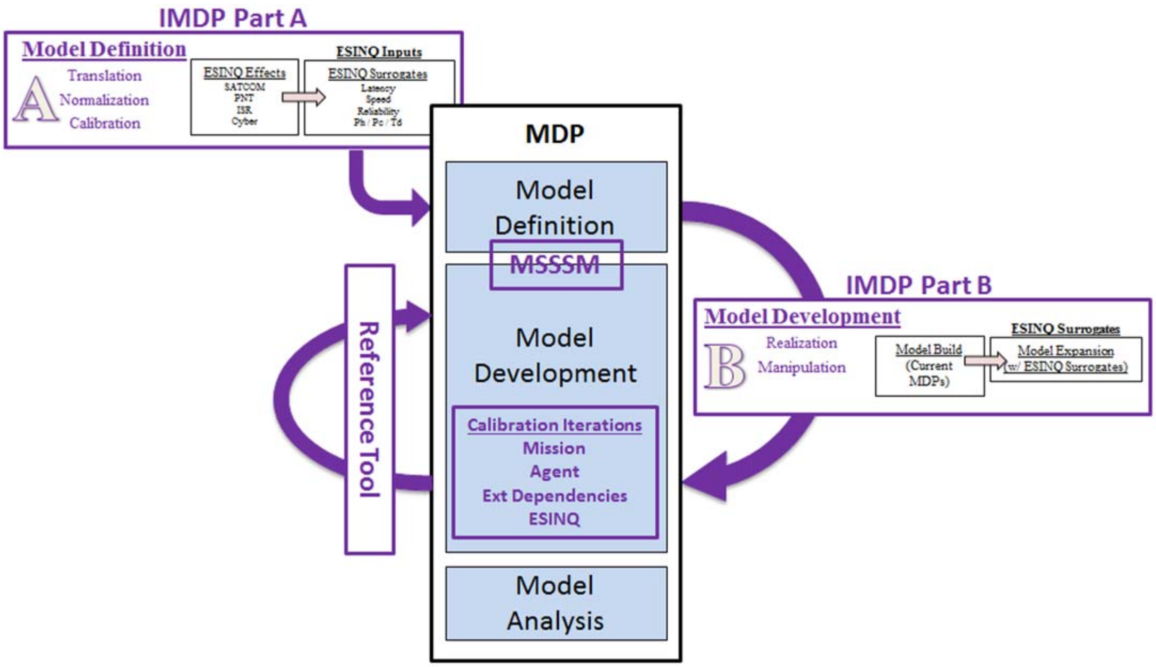


Figure 41. Applying the IMDP to the MDP

First, part A of the IMDP formalizes the process for bounding ESINQ factors by better defining the interactions of the system with the external environment during model definition. Part A expands and provides more structure to the weakly defined model definition step of traditional MDPs, and provides a means for accounting for both external dependencies and ESINQ effects in the model referent. Second, part B of the IMDP formalizing the process for implicitly representing this improved definition during model development, and supports a more accurate representation of the OE in the model. part B defines the implicit modeling process for iteratively implementing the improved referent developed in part A using surrogate factors, and enables the calibration and modeling of external dependencies and ESINQ effects. Third, and while a standalone process from the IMDP, a formalized methodology for screening and selecting of an appropriate M&S packages is provided, which guides the user to the selection of a more appropriate M&S packages, a step that is typically ignored during MDPs. The combination of these three improvements to current MDPs allows for a more complete understanding of the system, to include external dependencies, ESINQ effects, and non-traditional systems and their interactions with the environment within the model, as well

as a more complete investigation of the system trade-space. Now let us look at how the traditional MDPs were expanded to create the IMDP.

2. Overview

The end state of this research is to improve current MDPs and MBSE analysis methodologies by formalizing the process for accounting for ESINQ factors within a model. By accounting for ESINQ factors during model development, the resulting models will more accurately describe the system and its interactions with the OE, and provide the user more novel insights into the operations of the system of interest. Thus, through implementation of the IMDP, it is possible to bound and capture ESINQ factors which were largely ignored in the past, yielding a more accurate representation of the OE within the model. This more complete understanding of the system could then be incorporated into MBSE analysis methodologies by integration and use of these more refined models, and thus, provide a more accurate data set from which analysis can be performed. This is demonstrated in Figure 42, which highlights the improved synchronization of M&S, MBSE, and TSE through the execution of the IMDP.

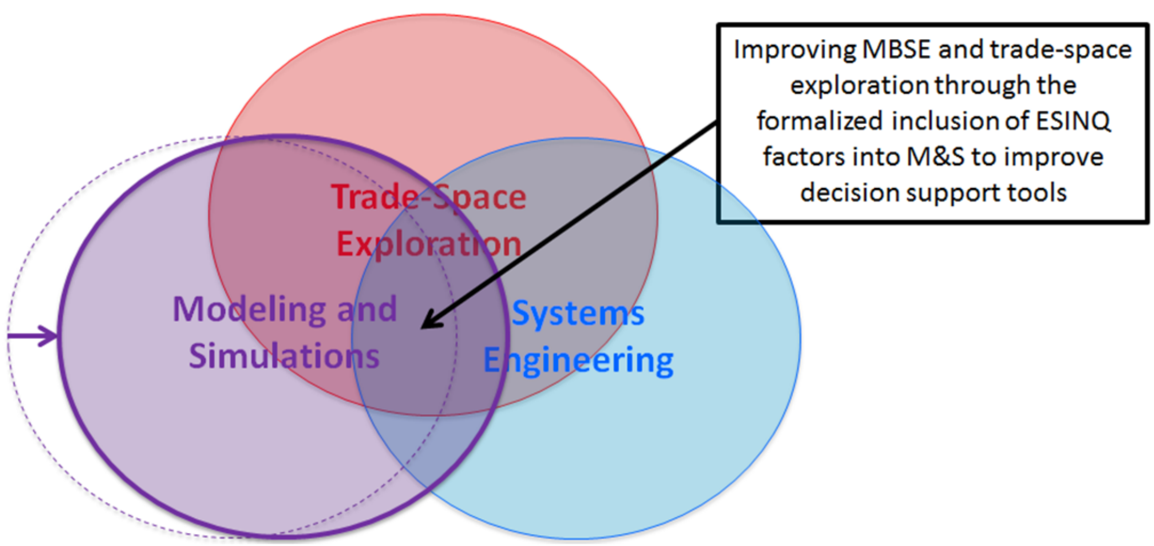


Figure 42. Pugsley’s Expansion of SE Analysis Methodologies

The IMDP developed in this work further expands the efforts of MacCalman and Beery by formalizing a MDP that can account for ESINQ factors, and then using this improved model to support a more accurate MBSE process. This improved understanding of the OE will result in more accurate model development, and thus, a more accurate and complete MBSE and TSE processes. The key to achieving this outcome, as well as the other secondary contributions discussed in Chapter I, is the ESINQ-enabled model. Unfortunately, as depicted in Figure 22, most traditional MDPs do not account for ESINQ factors because they reside outside of the internal and external model input sources typically considered during model development. Thus, in order to achieve the ESINQ-enabled model that is central in obtaining the outcomes of this dissertation, an implicit MDP was needed to formalize the process for expanding the model input sources to capture/bound ESINQ factors within a model. The IMDP developed in this work serves to achieve this need, and by following the conceptualized process outlined in Figure 43, model developers can produce ESINQ-enabled models.

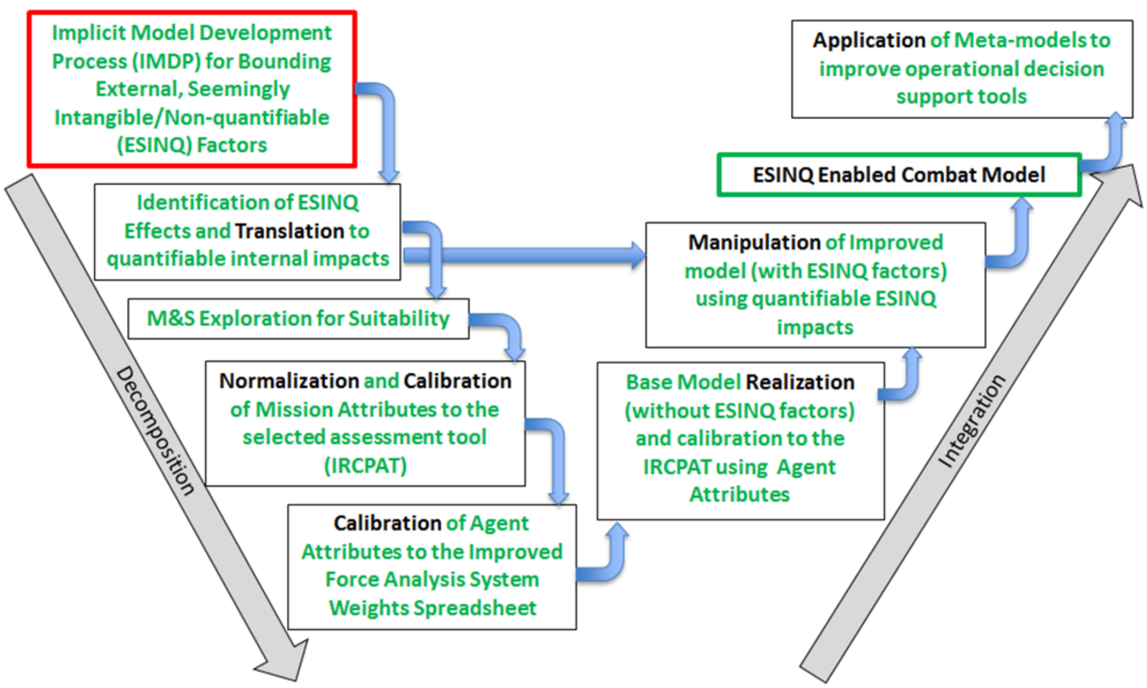


Figure 43. IMDP Conceptual Flow

The IMDP conceptual flow depicts a generalized framework for capturing ESINQ factors of interest and translating them into the model. This conceptual flow consists of five general processes, and includes Translation, Normalization, Calibration, Realization, and Manipulation. Application, although noted in Figure 43, is outside the scope of the IMDP, however will be explored in Chapter V. This conceptual process is similar to Beude’s (2000) description of Forsberg and Mooz’s “Vee” diagram (10), in that the “decomposition phase” focuses on the process of breaking down, identifying, and quantifying ESINQ factors (functions that the model must represent), while the “integration phase” focuses on the building up, integration, and expansion of the model (synthesis representation of those ESINQ functions) to develop the ESINQ-enabled model. This conceptual flow diagram captures the essence of what the IMDP is attempting to accomplish, and through expansion and clarification of its terms, which can be seen in Table 3, will serve as the foundation for the contribution of this work.

Table 3. IMDP

Part	Phase	Step	Description
Part A	Translation	1a	List and describe the primary external, and seemingly intangible and non-quantifiable effects in which you are trying to represent. (Use EEMM)
Part A	Translation	1b	Identify and list the tangible impacts on combat operations which the effects in Step A would likely have. (Update EEMM)
Part A	Translation	1c	Using the MSSSM, investigate potential Combat Models and identify a Model with appropriate factors which can best model the tangible impacts from Step 4B, that can be used as surrogates for the intangible effects. For the rest of this methodology I will be using MANA as my M&S package. (Update EEMM)
Part A	Normalization	2a	Selection of a reference tool
Part A	Normalization	2b	Base Line the Force Analysis System Weights Spread sheets to account for C4I contributions to combat power, then break this contribution into both external and internal contributions (If using the Improved Relative Combat Power Assessment Tool (IRCPAT), skip this step, this has already been done.
Part A	Calibration	3a	Baseline Calibration. Build a simplified model and instantiate the reference tool.
Part A	Calibration	3b	Calibrate the "Mission Attributes" to establish the baseline mission specific attributes for each agent for the selected model and mission set.
Part A	Calibration	3c	Calibrate the "Agent Attributes" for each agent to account for variations in capabilities based on the Improved Force Analysis System Weights Spread sheets to create the final "Agent Attributes" to be used in the Model.
Part A	Calibration	3d	Calibrate the "External Dependency Attributes" for each agent to account for internal dependencies on external sources for the generation of internal combat power to create the final "ExtDep Attributes" to be used in the Model.
Part A	Calibration	3e	Calibrate the "ESINQ Attributes" to establish the baseline ESINQ specific attributes for each agent for the model.
Part B	Realization	1a	Develope the model to improve its capacity to meet user needs and requirements, without any modification to the ESINQ factor surrogates from Mission/Agent/ExtDep/ESINQ calibration identified in Part A. This is an iterative process where you build model capacity by adding in other modeling aspects ignored during calbration, like other forces. Conduct analysis as needed to adjust and fine tune the model. 1000 Iterations of the model should be calibrated to within (+/- 5%) of the output from the IRCPAT. To verify, execute a 1 x factor DOE to establish a analysis reference point for future comparison.
Part B	Manipulation	2a	Expand the model to include the ESINQ factors identified in Part A by modify the ESINQ factors from their baseline values to a setting which achieves the expected impacts from each ESINQ effect. This task supports the development of operational support tools.
Part B	Manipulation	2b	Execute a full 2nd Order NOLH DOE across all Force Ratios to establish a new analysis reference point, used to quantify the operational impacts from the ESINQ effects of interest across all full range of severity. Same DOE process as described in Part A3b-e.
Part B	Manipulation	2c	Quantifying ESINQ Effects: Data analysis and Meta-model development for the responses of the ESINQ factors, quantifying operational impacts. Same Analysis process as described in Part A3b-e.

The IMDP expands traditional MDPs by providing a more formalized methodology for model development by expanding the level of guidance and detail driving model development, specifically with regard to the model definition. For consistency with traditional MDPs the IMDP is broken down into two general steps. The model definition step (part A: decomposition) describes the process where ESINQ factors are identified, translated, normalized, and calibrated in preparation for inclusion into the model. This is where the shortcomings noted earlier are addressed, and through a formalized IMDP, will provide the ESINQ-enabled data that will drive the model development in part B. The model development step (part B: integration) describes how the model is developed and then expanded to integrate the ESINQ factors refined during

part A, to include the generation of meta-models to drive tool development. Each of the steps described here has an additional sub-sheet associated with it that clearly articulates the process for the user to execute the IMDP, which will be described in detail later in this work. The intent of the IMDP is to expand traditional MDPs by supporting a broader investigation of a given system and its OE, specifically enhanced to address and bound ESINQ effects within the model. This improvement greatly enhances the usability of current MDPs, and allows users to capture a more complete understanding of the system of interest, as well as its interactions with the OE and ESINQ factors. With a general overview of the IMDP completed, a more in depth description of the IMDP is needed to provide the required detail needed to fully execute the methodology.

3. Presentation

To avoid any unnecessary duplication between this description and other parts of this work, a more generalized approach to presenting the IMDP is taken here. Specifically, this chapter provides the reader a complete introduction to the steps of the IMDP in order to provide a solid understanding of the process, but will forgo any significant detail. Additionally, to keep this description concise, the products described here will provide only enough detail to articulate the conceptual processes, and are not meant to serve as executable documents for the development of the model. In later chapters, Chapter IV: IMDP Demonstration, and Chapter V: IMDP Application, the description provided here will be expanded to include more detail.

a. Part A: Model Definition

The purpose of the model definition step is to provide a formalized methodology that enables model developers to produce translatable definitions of ESINQ factors of interest for inclusion into models. Because of the nature of ESINQ factors as described in Chapter II, they cannot be directly implemented into models due to the inability to translate them into a form acceptable by most models. The majority of models simply lack the freedom in attributes to accurately model factors that were not envisioned during the models original development. Once you attempt to use a model for something other than the original purpose, like modeling ESINQ factors, you are limited to the original

attributes, which are more often than not inadequate for the unforeseen purpose. This is further complicated by the fact that the majority of ESINQ factors reside in domains outside of the ground domain (the context for which defines the referent for ground combat models), which induces a significant amount of aggregation and simplification errors due to cross domain translation. To clarify this, consider the inclusion of a satellite into a ground combat model. To model a satellite in a ground combat model would be difficult to say the least, primarily because even though the model may have 100s of attributes that can be used to accurately characterize a tank or artillery, these attributes are typically not very useful for defining a satellite. Not only does the combat model lack adequate factors and settings to accurately represent the satellite, because the effects of the satellite are typically measured using MOEs from a different domain, the impacts of that satellite on the combat model are difficult to quantify as well. When attempting to represent ESINQ effects in models directly, these cross domain translation issues typically yield an undesirable representation of the OE, which often preclude their inclusion. The general steps of part A of the IMDP are described in Figure 44.

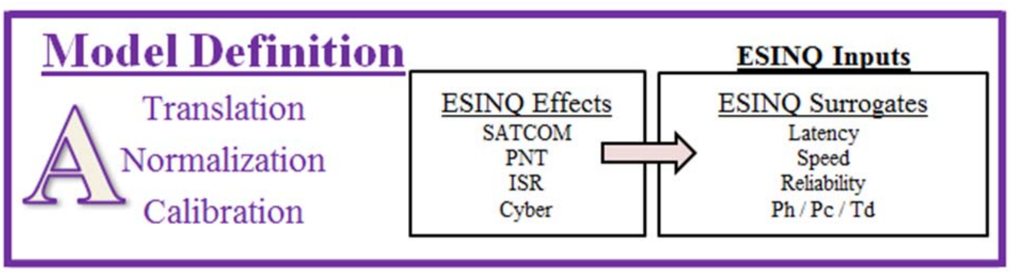


Figure 44. IMDP (Part A)

Part A of the IMDP expands the capabilities of current MDPs and MBSE analysis methodologies by formalizing the process for “bounding” ESINQ effects in a manner which more accurately translates to models than traditional MDPs allow, thus increasing the accuracy of the models referent without increasing the models complexity. The IMDP does this through the formalized translation, normalization, and calibration of modeling input factors with the goal of improving the overall accuracy of the model through a

directed manipulation of the supporting data. A detailed description of part A of the IMDP can be seen in Table 4.

Table 4. IMDP Part A

Part	Step	Description	Process
Part A	1a	List and describe the primary external, and seemingly intangible and non-quantifiable effects in which you are trying to represent. (Use EEMM)	Translation
	1b	Identify and list the tangible impacts on combat operations which the effects in Step A would likely have. (Update EEMM)	
	1c	Using the MSSSM, investigate potential Combat Models and identify a Model with appropriate factors which can best model the tangible impacts from Step 4B, that can be used as surrogates for the intangible effects. For the rest of this methodology I will be using MANA as my M&S package. (Update EEMM)	
	2a	Selection of a reference tool	Normalization
	2b	Base Line the Force Analysis System Weights Spread sheets to account for C4I contributions to combat power, then break this contribution into both external and internal contributions (If using the Improved Relative Combat Power Assessment Tool (IRCPAT), skip this step, this has already been done.	
	3a	Baseline Calibration. Build a simplified calibration model and instantiate the reference tool.	Calibration
	3b	Calibrate the "Mission Attributes" to establish the baseline mission specific attributes for each agent for the selected combat model and mission set.	
	3c	Calibrate the "Agent Attributes" for each agent to account for variations in capabilities based on the Improved Force Analysis System Weights Spread sheets to create the final "Agent Attributes" to be used in the final Model.	
	3d	Calibrate the "External Dependency Attributes" for each agent to account for internal dependencies on external sources for the generation of internal combat power to create the final "ExtDep Attributes" to be used in the final Model.	
	3e	Calibrate the "ESINQ Attributes" to establish the baseline EINQ specific attributes for each agent for the selected combat model.	

Part A of the IMDP can be broken down into three primary processes, and include Translation, Normalization, and Calibration, which can in turn be broken down into lower level sub-steps (parts A1a – A3e). While these lower level sub-steps and their associated products will only be briefly described here, they will be demonstrated in detail in Chapter IV, and the link to the complete IMDP can be found in the Supplemental of this work. The intent of this section is to provide the reader with a description of the conceptual flow described in Figure 46, specifically by providing more detail regarding the functions of each of the three primary steps. For brevity, the complete demonstration of the process will not be documented here; any tables and figures discussed here are for explanatory purposes and are not meant to represent the fully articulated process of part A, which will be demonstrated in the next chapter.

(1) A1: Translation

The intent of this sub-step of the IMDP is to translate what would be considered an ESINQ factor or effect into a form which can be understood and implemented by the model. As described in Table 4, Translation has three primary steps, and begins with the

identification of the ESINQ effects in which the user is interested in accounting for within the model. Once these ESINQ effects have been identified, the IMDP leads the user through the mapping of these ESINQ effects to tangible effects and outcomes that can potentially serve as surrogates for the ESINQ effects within the model. Once these tangible effects have been identified, the IMDP directs the user through a formalized M&S package screening process where a suitable M&S package is selected that can best meet both the users' primary intent for the study as well as address the ESINQ effects of interest. Once the M&S package is selected, the tangible effects which were mapped earlier are assessed for applicability to the selected M&S package, appropriate factor surrogates are selected. A brief overview of these three steps follows.

A1a: Identifying ESINQ Effects and Expected Impacts

The intent of this step is to build an understanding of the ESINQ effects in which the user is trying to implement in the model, as well as the expected impacts that these effects would likely have. This step has three primary sub-steps which facilitate an expanded understanding of the ESINQ factors of interest, and begins with the user defining the purpose and intent of the study through the development of the Operational Concept (OC). As defined by Buede (2009), the purpose of the OC is to codify a shared vision of the system that characterizes what the system is, what it does, and how it will be used. The OC will codify the overarching goals and end-state of the M&S study, and will serve to aid the user in maintaining his/her perspective when identifying ESINQ factors of interest as well as selection of an appropriate M&S package. While the OC is often synonymous with the Use Case, a SE analog typically used to describe the vision for an emerging system design, for this work the OC will refer to the operational and synthesis models, while the Use Case will be reserved for defining the vision for the physical system. Once the operational concept is defined, and the context and boundaries of the study established, ESINQ factors of interest can then be identified based on the users' needs and the definitions established during Chapter I. Here, users will identify the overarching ESINQ factors of interest to their study. This initial identification should be broad in scope, and focused on capturing the essence of the effects in which the user wishes to explore, without any consideration for the feasibility of capturing those effects.

Once the ESINQ effects of interest are identified, the user will then describe in much more detail the expected impacts that these ESINQ factors will have within the context of the operational scenario of interest. The detail here is similar to brainstorming, and should include any and all potential impacts, regardless of the appropriateness, based on the purpose of the study. The intent is to generate a large set of potential impacts to build a better understanding of the ESINQ effects prior to identification of tangible effects. The end-state of Step 4A is the creation and instantiation of the ESINQ Effects Mapping Matrix (EEMM) located in IMDP. This is the primary tool used during the IMDP, and serves to translate ESINQ factors of interest to tangible and compatible factors within the selected model. With the ESINQ factor of interest identified, and the expected impacts codified, we can now link these expected impacts to tangible operational effects.

A1b: Linking ESINQ Expected Impacts to Tangible Effects

The intent of this sub-step of the IMDP is to refine the understanding of the ESINQ impacts gained during A1a, and link them to a set of tangible effects that can potentially be used to represent them within the model. The IMDP accomplishes this by guiding the user to a better definition of the ESINQ effects of interest through a process of brainstorming and subjective assessment. This step builds more detail regarding the expected impacts of the selected ESINQ factors, and produces a linked list of potential effects that can tie expected impacts to tangible effects within the model. While the user focused on establishing the broad interest of the study in Step A1a, the intent here is to capture a much more detailed understanding of the tangible effects that can potentially represent the ESINQ effects of interest. This is important because we have yet to select an M&S package, and the understanding gained here will help screen and select an appropriate M&S package for use within the study. Following the identification and codification of these tangible effects, the EEMM is expanded to demonstrate the linkages between expected impacts and a set of newly determined tangible effects that can potentially be used within the model to represent the impacts to operations from the ESINQ factors. With a better understanding of the tangible effects which we believe could be used to represent the impacts from ESINQ factors within the model, we can now review potential M&S packages for appropriateness, and select one for use.

A1c: M&S Suitability Assessment and Selection

The intent of this sub-step of the IMDP is to investigate potential models and select one for use that has sufficient flexibility to represent the tangible effects identified in Step A1b, which can then be used to act as surrogates for the intangible impacts identified during Step A1a. The IMDP accomplishes this by providing the user with a formalized methodology for assessing the feasibility of potential M&S packages for use within a particular study. This methodology, which will from this point on be referred to as the MSSSM, can be found in Appendix A. The MSSSM provides the user a the means for framing his/her needs of an M&S package, and following this conceptualization, the MSSSM moves the user through the review, screening, exploration, assessment, and finally, the selection of an appropriate package for use within their study. Though the MSSSM is time consuming, it has the potential to greatly increase the accuracy of the M&S study by limiting the potential errors introduced through the use of non-optimal M&S packages. While the MSSSM is not required to execute the IMDP, if time and resources are available it is recommended.

Following the completion of the MSSSM, a weighted decision matrix will be produced that will allow the user to compare the top three M&S packages through a total value score based on the needs and weights of the user. For this dissertation, the MSSSM was used to select Map Aware Non-uniform Automata (MANA) as the M&S package for this research, which was developed by McIntosh et al. (2007) on behalf of the New Zealand Defense Technology Agency. While not described in detail here, all 60+ pages of that MSSSM assessment can be found in Appendix A. Following the selection of an appropriate M&S package for use within the study, as well as the identification of the surrogate factors that can best represent the tangible effects described in Step A1b, the EEMM is expanded to demonstrate the mapping between tangible effects and surrogate factors within the selected model. This mapping serves two purposes. First it identifies which surrogate factors can represent the most tangible effects, which supports weighting of factors. Second, the mapping ensures traceability from surrogate factors, through tangible effects and expected impacts, back to the original ESINQ factors of interest.

The intent of the translation sub-step of the IMDP was to manipulate ESINQ factors into a form which could be understood and implemented by the model. Translation lead the user through identification of the ESINQ factors of interest, their expected impacts linked to a set of tangible effects, the selection of an appropriate M&S package, and the identification of surrogate factors to represent the effects of the ESINQ factor. Translation left the user with a better understanding of the surrogate factors that could be used to represent the impacts from ESINQ factors within the model, as well as the selection of an appropriate M&S package based on the needs of the study and the availability of surrogates for the ESINQ effects of interest. With this understanding, we are ready to move on to the next step of the IMDP, which is Normalization.

(2) A2: Normalization

The intent of this sub-step of the IMDP is to normalize the reference tool that will be used to calibrate the selected model in the next step. In order to establish an accurate baseline for calibration and the subsequent model development, any ESINQ-enabled bias in the reference tool must be stripped out before implementing the model development to ensure that confounded factors are minimized. Normalization has two primary steps, and begins with the selection of an appropriate reference tool, typically one which the users use for operational assessments. This can be an assessment tool, as used in this work, or another model. After the reference tool is selected it must then be normalized to establish a base-line by separating out the internal and external sources of combat power. Because the modeling of some systems may be based on data that includes combat power derived external to the system boundary, it may be required to decouple both internal and external effects in order to support a better articulation of the actual sources of combat power. At the conclusion of this sub-step, the selected reference tool has been normalized and is ready for use to calibrate the surrogate effects identified in the translation step.

A2a: Selection of a Reference Tool

The intent of this step is to select an appropriate reference tool for use during the calibration and validation of the model. While the reference tool is not technically required to execute the IMDP, it ensures a more accurate assessment of the ESINQ

effects within the model, the analysis derived from that model, as well as provides some level of validation, depending on the validity of the reference tool. Executing the IMDP without a reference tool would lead to a highly subjective process that cannot be guaranteed to improve the accuracy of the model. The IMDP provides a framework that supports the selection of a reference tool by providing the user with considerations that will help guide them through the screening and selection of an appropriate reference tool based on the intended need. This directed exploration of potential tools is much more likely to produce an appropriate tool than would have been achieved without the use of the IMDP. For this dissertation, the IMDP led to the selection of the Army's FRC as the reference tool for this work, which will be discussed in more detail in the next chapter.

A2b: Normalization of the Reference Tool

The intent of this step is to establish an accurate baseline for the calibration and development of the model by removing any potential ESINQ-enabled bias from the reference tool. Any bias left in the reference tool will be passed on to the model following calibration, and thus, degrade the accuracy of the model to represent the impacts from the ESINQ factors we are interested in. Thus, the user must inspect the source data of the reference tool in detail, and ensure that any such bias is removed to ensure that confounded factors are minimized. The source data that drives the FRC is based on the COFM and expanded by the Army's Forces Analysis-System Weights and Normalization (FA-SWN) spread sheets, which were obtained from the National Training Center (NTC) Lizard Team by request. Unfortunately, each reference tool can have a vastly different set of source data, and thus, it is impossible to provide a formalized methodology for stripping out this bias. To overcome this issue, the IMDP provides a general framework and example to guide the user through the identification and removal of bias from the source data of the reference tool. Once the bias is removed, we can update the source data of the reference tool with these improved values, creating an improved FRC that better captures the system level contributions to combat power, yielding a better system versus system representation of combat. With normalization of the reference tool complete, we can now calibrate Mission, Agent, External Dependence (ExtDep), and ESINQ factors in the model.

(3) A3: Calibration

The intent of this step of the IMDP is to incrementally calibrate the surrogate ESINQ factors selected during translation of the reference tool to link the outcomes of the model to the selected reference tool. Additionally, because the reference tool in this case, the Improved Relative Combat Power Assessment Tool (IRCPAT), includes dependencies on mission sets as well as system specific attributes; mission and agent factors will also need to be calibrated. It is this complexity that makes calibration the most complicated step within the IMDP, and depending on the user's requirements, can demand a significant amount of effort. The general flow of the calibration sub-step can be seen in Figure 45.

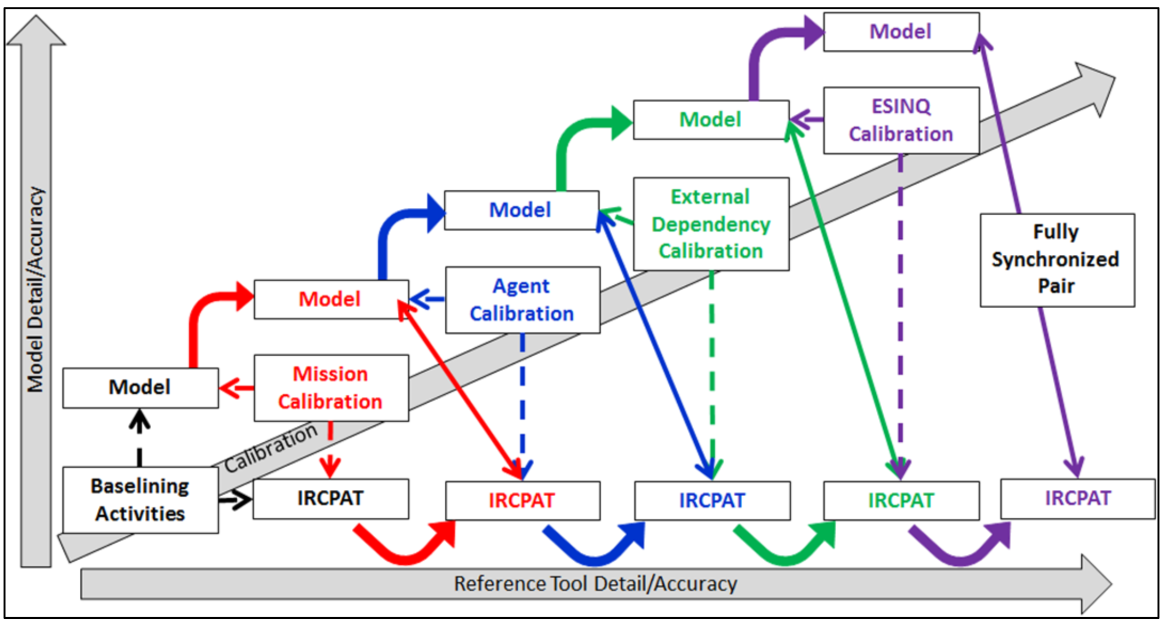


Figure 45. Calibration Building Blocks

Calibration begins with baselining activities, where we prepare both the reference tool and the model for use. From this point forward, we begin an incremental spiral development process where we expand the capabilities and accuracy of the model and the reference tool while maintaining their synchronization. The IMDP accomplishes this by directing the user through a series of design iterations, and using DOE and statistical analysis tools, conduct increasingly detailed design space exploration to establish the

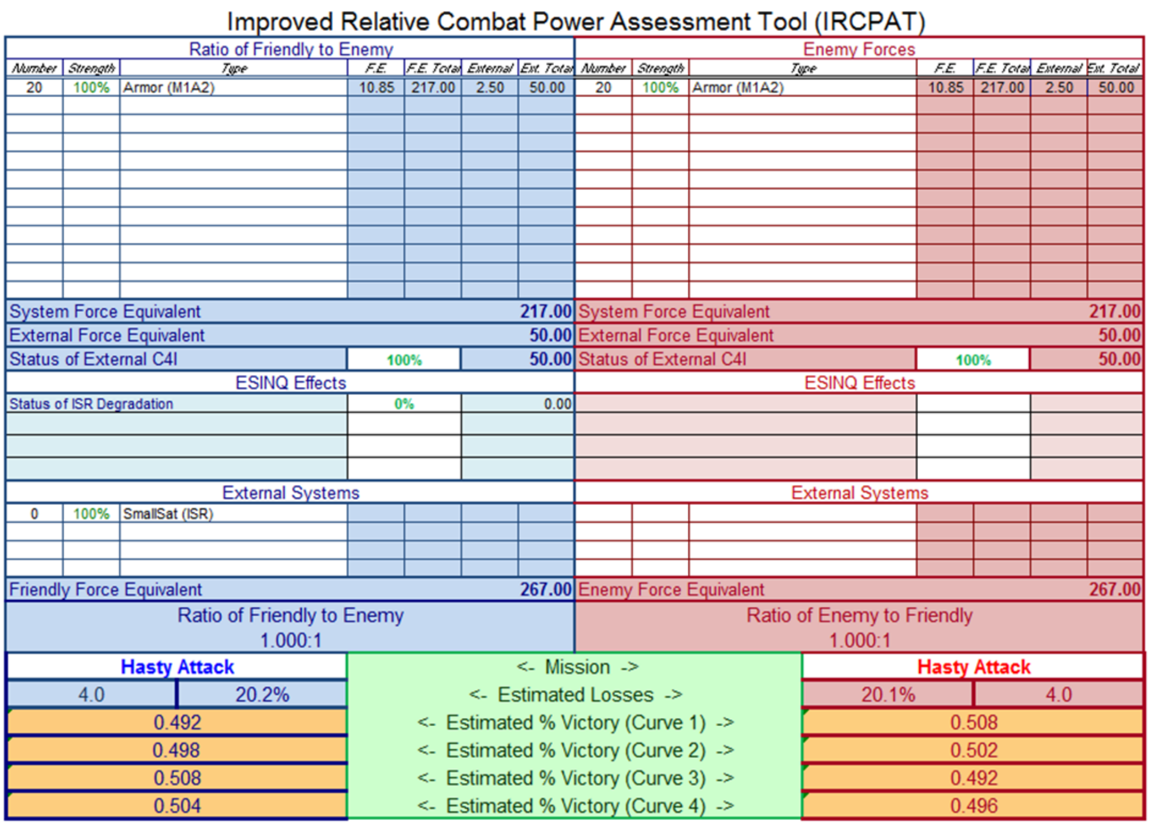
mission, agent, external dependencies, and finally the ESINQ attributes for each agent. The first of these iterations is Mission Calibration, where the model and reference tool are expanded and calibrated to account for the impacts from the selected mission sets on Blue Probability of Victory (P_v), which quantifies the defensive advantage. The next iteration is Agent Calibration, where the model and reference tool are expanded and calibrated to account for the system level (Agent) differences between opposing forces, which quantifies the advantages due to system capabilities. The third iteration is ExtDep Calibration, where the model and reference tool are expanded and calibrated to account for each agent's dependency on external factors for the generation of internal combat power. The final iteration is ESINQ Calibration, where the model and reference tool are expanded and calibrated to account for the baseline values of the ESINQ surrogates of interest, which will be used in later steps as a reference point for quantifying operations impacts. A full description of the steps of calibration will be provided here while avoiding as much redundancy as possible. Thus, to avoid the inherent replication of the IMDP Calibration steps, it will not be presented linearly as it was intended to be executed. Rather, the process will be covered in a single iteration, with the specifics of Mission, Agent, ExtDep, and ESINQ calibration being discussed as needed to describe the differences between the steps. For more detail regarding the complete process, please refer to Chapter IV, Demonstration and Analysis as well as in the IMDP Part A3a-e. Let us begin calibration by discussing baselining activities.

A3a: Baselining Activities

The purpose of baselining is to establish a foundation for the incremental calibration of mission, agent, external dependencies, and ESINQ factors that will follow. This step focuses on the preparation and development of the simplified model and reference tool needed to begin calibration. Baselining activities has three primary steps, first, to instantiate the reference tool, second, to develop and calibrate the simplified model to the reference tool, third, to establish the FR attributes to be used in the DOEs. Each step will be briefly discussed, starting with the instantiation of the reference tool.

To instantiated the reference tool, the FRC is modified to establish a baseline for calibration, which is a simplified scenario where we will minimize all variables other

than the mission set and Force Ratio, which will be ignored in the baseline. This will provide a starting point for quantifying the operational impacts from the mission set on metrics of effectiveness, as well as linking the model to the reference tool. Because of the future intended purpose of this tool, and its current inability to represent the impacts from ESINQ effects, the FRC needed to be expanded and improve in numerous ways to make it useable for the purposes of this work. While these improvements and modifications will not be discussed here, they will be discussed and demonstrate in detail in Chapter V. The improved and expanded FRC, which will from this point forward be called the IRCPAT, and can be seen in a partial form in Figure 46. For a full description of the IRCPAT refer to Chapter V.



Improved Relative Combat Power Assessment Tool (IRCPAT)

Ratio of Friendly to Enemy							Enemy Forces						
Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total	Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total
20	100%	Armor (M1A2)	10.85	217.00	2.50	50.00	20	100%	Armor (M1A2)	10.85	217.00	2.50	50.00
System Force Equivalent						217.00	System Force Equivalent						217.00
External Force Equivalent						50.00	External Force Equivalent						50.00
Status of External C4I			100%			50.00	Status of External C4I			100%			50.00
ESINQ Effects							ESINQ Effects						
Status of ISR Degradation			0%			0.00							
External Systems							External Systems						
0	100%	SmallSat (ISR)											
Friendly Force Equivalent						267.00	Enemy Force Equivalent						267.00
Ratio of Friendly to Enemy 1.000:1							Ratio of Enemy to Friendly 1.000:1						

Hasty Attack			Hasty Attack	
4.0	20.2%	<- Estimated Losses ->	20.1%	4.0
0.492		<- Estimated % Victory (Curve 1) ->	0.508	
0.498		<- Estimated % Victory (Curve 2) ->	0.502	
0.508		<- Estimated % Victory (Curve 3) ->	0.492	
0.504		<- Estimated % Victory (Curve 4) ->	0.496	

(The centre cell of the header row reads "<- Mission ->".)

Figure 46. IRCPAT (Baseline)

As shown in Figure 46, the FRC was significantly modified to create a more robust and modern operational planning tool. Here we can see that the IRCPAT was

instantiated for the baseline case, which is two identical forces without any considerations for Mission, Agent, external dependencies, or ESINQ factors of combat power. This is seen in the equal force type and size, the equal mission type, and the zeroing out of all ESINQ sources of combat power in the IRCPAT. Thus, as expected, the IRCPAT shows a 1:1 Force ratio, with an expected Blue P_v of 50%. With the reference tool instantiated, it is now time to develop the simplified model.

The simplified model is a small controlled experimental environment that will support the analysis of the impacts from factors of interest on forces during calibration. The model will provide an abstract representation of the system of interest, accurately represent all interaction of the system with the external environment at a level of resolution appropriate to produce output data of enough fidelity to support the intended analysis. Using the M&S package selected during the execution of the MSSSM, the user develops the model to the requirements as outlined in the OC established during part A1c. The development of the model does not differ greatly from traditional MDPs other than the IMDP directing the user to address three specific considerations. First, the IMDP directs the user to use an increased number of agent attributes for later use during the calibration steps. Second, the IMDP directs the user to initially limit the number of differing agents and fix the majority of all attributes to better highlight the impacts of the select factors of interest on Blue and Red forces. Third, the IMDP directs the user to build the simplified model as accurately as possible, but without any external factors. This is key; all agent attributes that are expected to be used in the complete model must be instantiated in the simplified model with logical and defendable agent settings. Failing to establish agent attributes here (i.e., leaving default settings), and then attempting to modify the setting value later, after calibration, can have a significant impact on the accuracy of the model, and can introduce potential anomalies.

While the IMDP cannot provide a formalized process to do this, which would be impossible due to the nearly infinite amount of potential variables and user inputs in to the process, it does provide a framework. This framework supports the user’s selection of appropriate agent factors for use within the simplified model, as well as a list of key points that the user should consider when developing the model. This framework takes

the user through agent selection, model development, and then finally model verification, the detailed steps of which can be found in the IMDP. For baselining activities, this is a fairly straight forward process, requiring the development and verification of a model that has two identical sets of forces pitted against each other, without any advantage to either side being gained due to differences in Agent, Mission, ExtDep, or ESINQ factors. This billiard board modeling environment ignores all aspects of combat other than Force Ratio, and after verification, should yield a fairly consistent fight where the P_v converges on 50% for the Blue force when the RCP is 1:1. This should be confirmed through a 1000 replication verification run prior to moving forward. Following model development, the last step is to establishment of Force Ratio Attributes.

The purpose of establishing Force Ratio Attributes is to determine the range of Blue agents that will be needed to capture the full range of expected victory's based on the users selected mission set and modeling needs. For this work, this range would result in a P_v between 40% to 95%, which, based on the mission set, will help determine the number of agents. The IMDP provides a tool for determining these numbers in A3a, and using the Hasty Attack – Hasty Defense (HA-HD) mission set and its corresponding mission modifier (2.5), as well as the starting Red strength of 20, the tool recommends that the DOE should vary the number of Blue tanks from 46 to 83 to explore the full range of potential victory cases, with 50 tanks giving the Blue force a P_v of 50%. This Force Ratio factor and ranges will be the primary method to delineating numerical superiority in the DOEs used in future model exploration.

A3b-e: Mission/Agent/ExtDep/ESINQ Calibration

The intent of calibration is to expand and link the model and the reference tool through the establishment of Mission, Agent, ExtDep, and then ESINQ specific attributes that will capture the impacts that these attribute have on metrics of operational effectiveness within the model and reference tool. This is an iterative process, and when repeated during the spiral development of the model to account for Mission, Agent, ExtDep, and then finally ESINQ attributes, the process resembles the description seen in Figure 50.

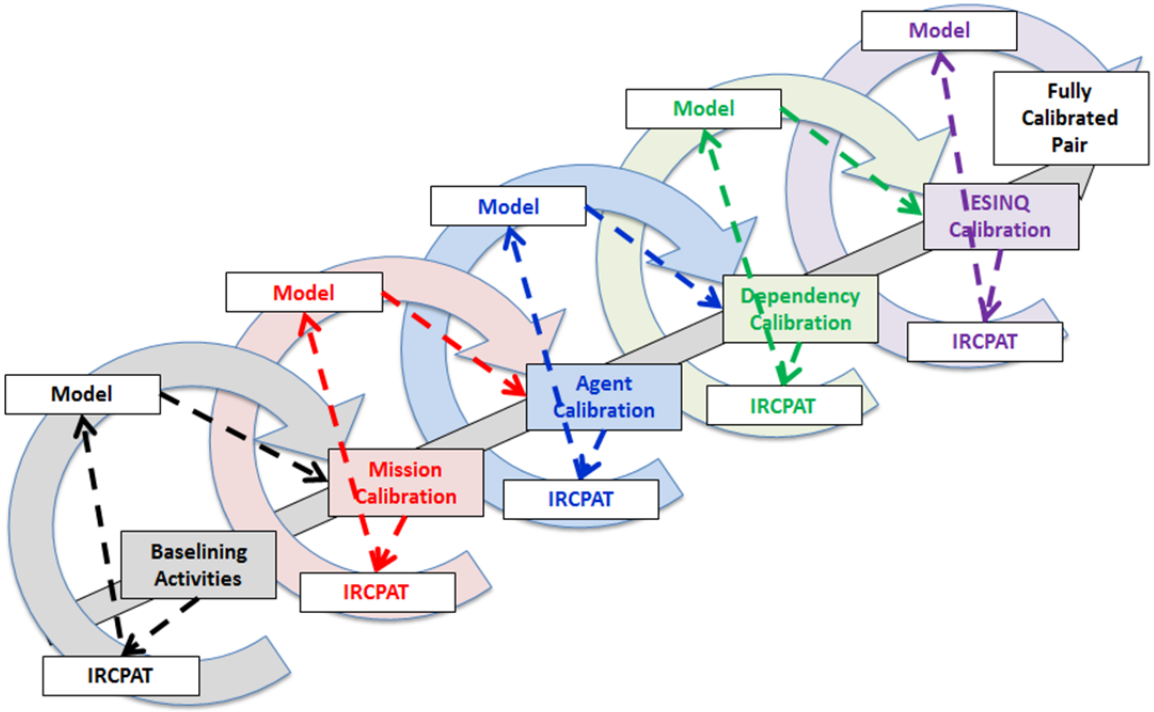


Figure 47. Calibration Flow

As shown in Figure 47, the calibration of all four attribute types (Mission, Agent, ExtDep, and ESINQ), is an iterative process, where the IMDP directs the user through the set of four primary steps. First, calibration begins with the expansion of the reference tool to include combat power contributions from the selected attribute. Second, the attribute factors of interest are selected, their ranges estimated, and then the model is expanded and updated to include these factors. This step is where the majority of the differences between the four iterations reside. Third, a multi-factor DOE is designed and executed to produce detailed output data that captures all factor interactions within the model with respect to impacts to metrics of combat effectiveness, which include P_v, Force Exchange Ratio (FER), and Loss Exchange Ratio (LER). Forth, analysis of the DOE output is then conducted in order to establish and record the factor values for the selected attribute which results in the least variation of the Blue P_v estimated by both the model and the reference tool across the full range of potential FRs. Regardless of the type of attribute we are attempting to calibrate, the calibration process will always have these same four primary steps. In fact, the steps of these four iterations are nearly identical, only differing

slightly in the method of calibration for each of the four attribute types. Thus, for brevity, the full calibration process will only be shown for a single iteration, highlighting the differences for each of the four attribute types. Let us begin with the expansion of the reference tool.

Expansion of the Reference Tool

The first iterative step is the expansion of the reference tool to account for the combat power contributions from each of the four attributes. To expand the reference tool, the IRCPAT is modified to include considerations for the selected attribute on Blue P_v. For Mission calibration, this expansion allows the reference tool to account for the impacts of Mission set on metrics of combat effectiveness. This quantifies the advantage of the defending force, which for this example was a Hasty Attack versus Hasty Defense. For Agent calibration, this expansion allows the reference tool to account for the impacts of systems specific capabilities on metrics of combat effectiveness. This identifies and accounts for the differences in opposing systems, like the differences between the M1A2 and the T80U used in our example, which quantifies the advantages gained from superior weapons systems. For ExtDep calibration, this expansion allows the model to account for the impacts of the external contributions to weapon system internal combat power derived from sources outside the system boundary, which are already accounted for in the IRCPAT. For ESINQ calibration, this expansion allows the reference tool to account for the impacts of ESINQ factors of interest on metrics of combat effectiveness. This initial expansion will only capture the baseline (no impact) of all ESINQ factors, and thus will not impact either the tool or model outcome at this point, but will be further expanded in part B of the IMDP to include the rest of the ESINQ factors of interest. The expanded IRCPAT following Mission, Agent, and ExtDep calibration can be seen in Figure 48.

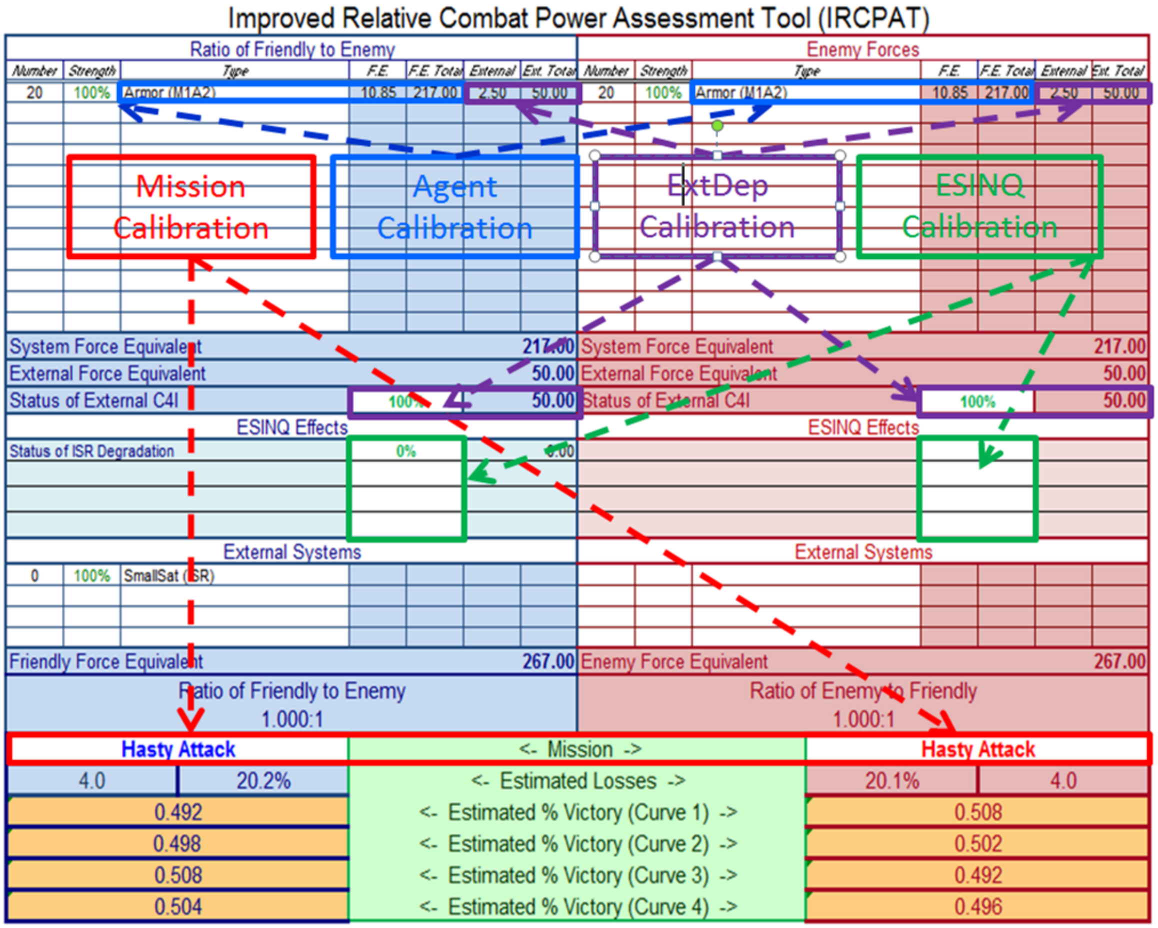


Figure 48. IRCPAT (Post Calibration)

As shown in Figure 48, the baseline IRCPAT was modified over three iterations (ESINQ calibration does not impact this tool) to account for the impacts of these attributes on metrics of combat effectiveness. First, the IRCPAT was modified during Mission Calibration, which established the selected mission set, which in this case, had the Blue force conducting a Hasty Attack and the Red Forces conducting a Hasty Defense. This yielded a significant advantage to the Red Force, who was defending, which dropped the Blue P_v from 50% to roughly 3%. Thus, to maintain the 50% P_v, the Blue Force Ratio was increased to 2.5 to 1, which required 50 Blue tanks versus the 20 Red tanks. Next, the IRCPAT was modified again during Agent Calibration, which took into account the differences between systems of the opposing forces, which in this case, had the Blue force operating M1A2s and the Red Forces operating TA-80Us. This

yielded an advantage to the Blue Force, who was operating a superior weapons system, which increased the Force Ratio from 2.5:1 to 2.95:1, and the Blue P_v from 50% to roughly 72%. Thus, to maintain the 50% P_v and a 2.5:1 Force Ratio, the number of Blue tanks was decreased from 50 to 42. Finally, the IRCPAT was modified one last time during ExtDep Calibration, which took into account the dependencies of opposing systems on external sources for internal combat power. This more accurately assesses the systems combat power by including both the systems combat power and external sources of combat power. Because the weapon systems of the Blue force (Tier I) derive more of their total combat power from external sources than the Red force (Tier II), this yielded an advantage to the Blue Force. This increased the Force Ratio from 2.5:1 to 2.79:1, and the Blue P_v from 50% to roughly 65%. Thus, to maintain the 50% P_v and 2.5:1 Force Ratio, the number of Blue tanks was decreased again from 42 to 38. With the reference tool expanded to account for Mission, Agent, and ExtDep attributes, it is now time to execute calibration and model expansion.

Expansion of the Model

Following the expansion of the reference tool, the second iterative step focuses on identify the attribute factors of interest, estimate the ranges of potential impacts, and then expanded and updated the model to include these factors. Because this process is heavily dependent on the type of attributes which we are calibrating (Mission, Agent, ExtDep, ESINQ), each iteration through this step is slightly different. Thus, of the four primary steps of calibration, this is the step where the majority of all differences reside. To ensure the reader understands the complexity of this step, each of the four calibration iterations will be discussed individually, starting with Mission calibration.

The IMDP leads the user through Mission calibration by providing the user a set of generalized steps that allow for the classification of the range of impacts from the surrogate factors being used to represent the impacts of Mission set on metrics of combat effectiveness. To do this, the IMDP provides a tool that directs the user through five general steps, which include: the establishment of a relative hierarchy of impacts; the identification of Mission set values; the estimation of the maximum impacts from these

factors; the establishment of the DOE ranges for these Mission factors; and finally the expansion of the model. This process is described in Table 5.

Table 5. IMDP Part A3b: Mission Attributes

Impact Hierarchy

Mission Set Transfer

Estimated Max Values

Establish DOE Ranges

Update the Model

2 Mission Calibration: These are attributes of each agent that are tied to the mission set, these help define "advantage" of defending forces. Determine the range of the Mission Attributes based on the specified mission set of each force by selecting the appropriate input values (Yellow cells) in the following table. If you do not wish to use this DOE calculator and already have an understanding of the required factor ranges, input them directly into the next table.

- For this example, the following multiplication factors were used.

Modifiers	HA	DA	HD	DD	Ph Combo Mod Max		
Pers Conc	0.30	0.40	0.60	0.80	DD-HA	1.00	0.12
Ph Against	1.00	0.90	0.60	0.30	DD-DA	0.90	0.18
Ph From	0.40	0.60	0.90	1.00	HD-HA	0.90	0.24
RateOfFire	0.40	0.60	0.80	1.00	HD-DA	0.81	0.36
Speed	0.60	0.80	0.00	0.00	HA-HA	0.40	0.40

- Transfer these values to the "Mod" column in the DOE Factor Setting Tool Below.
- Insert your "Maximum" values (in the format accepted by the model for that factor) into the DOE Tools based on knowledge and expected performance of the systems being modeled.
  - o Blue Hasty Attack vs. Red Hasty Defense

	Mod	Max	DOE Low	Model	DOE High
Blue Concealment	0.30	90	10	27	57
Red Concealment	0.60	90	24	54	84
Blue Ph (at 3500m)	0.24	0.40	0.05	0.10	0.30
Red Ph (at 3500m)	0.90	0.40	0.16	0.36	0.40
Blue RoF (#/100)	0.40	30	5	12	27
Red RoF (#/100)	0.80	30	9	24	30
Blue Speed	0.60	48	10	29	48
Red Speed	0	0	0	0	0

As shown in Table 5, the purpose of this step is to select and establish the range of Mission Attributes that will be used to represent the impacts of the Mission set on the model. Simply speaking, these are the attributes that will be used to quantify the "advantage of the defense" within the model. The four factors shown here were identified during the author's investigation of MANA, and were selected for their ability to manipulate model outcomes without inducing significant complexity. These factors include Personal Concealment (P_{con}), Probability of Hit (P_h), both against and from, Rate of Fire (RoF), and Speed. While this work recommends that the user of the IMDP use the same factors, some modifications or alternatives may be needed based on the selected M&S package and needs of the user. To execute this step, the user begins by inputting the expected relative impacts of each of the five factors in the four general mission areas.

From this, the tool calculates the P_h Combo Mod that accounts for the specific mission type combination, of which there are nine possible combinations. The user then transfers the specific mission type values of interests (HA-HD for this example) into the DOE Mod column, as well as the P_h Combo Mod, and after inputting the maximum estimated value each of these factors can have, the min and max values for each of the four factors (Red and Blue) are calculated. The last step is to expand the model to account for these new factors, and to conduct a verification run to ensure that the model remains synchronized with the expanded reference tool. After the model verification, the model is ready for DOE and analysis, which will account for the differences between opposing forces based on the Mission set, and will be discussed in later. Following Mission calibration, the model can now be expanded yet again through Agent calibration.

The IMDP leads the user through Agent calibration by providing the user a set of generalized steps that allow for the identification of new Agent factors as well as modification of existing Mission factors to represent the system specific differences between opposing forces. To do this, the IMDP provides a tool that directs the user through five general steps, which include: system comparison; assessment of the system differences; quantification of these differences; establishment of the DOE ranges; and finally the expansion of the model. This process can be seen in Table 6.

Table 6. IMDP Part A3c: Agent Calibration

System Comparison

Delta Assessment

Delta Quantification

Establish DOE Ranges

Update the Model

2 Agent Calibration: Calibrate the Agent Attributes for each agent to account for variations in capabilities based on the Improved Force Analysis System Weights Spread sheets to create the final "Agent Attributes" to be used in the Model.

- Compare the system attributes using the source documents of the reference tool.
  - o Capture the differences between these agents in a table. These 5 areas, and associated
    1 System Attributes (speed)
    2 Protection Attributes (Enemy Ph, Concealment)
    3 Weapons Attributes (Ph)
    4 Secondary Weapons Attributes (Ph)
    5 C4SI (Td, Pc)
  - o The completed assessment of the system differences can be seen below. In this

Attribute	Weight	M1A2	T-80U	+/- 5%	Modeled?	Calibrate?
System	0.25	0.17	0.17	0.0%	Yes	No
Protection	0.35	0.38	0.28	26.3%	No	Yes
Weapons	0.35	0.21	0.22	-4.8%	Yes	No
Aux Weap	0.05	0.08	0.05	37.5%	No	No
Inter C4I	N/A	0.25	0.201	19.6%	No	Yes
F.E. x10	1.00	10.90	9.21			

  - o Note: Internal C4I comes from Step A2b (Internal C4I FE), and accounts for roughly 23% of
  - o Determine if the model needs to be calibrated to account for them. If the system
  - o Quantify the changes to agent attributes needed to represent the system differences.
    M1A2 are 26.3% more protected than the T-80U, so reduce the T-80s Ph by 26.3%
    M1A2 Aux Weapons are 37.5% better. If weapons are modeled individually, disregard,
    M1A2 has 19.6% better sensors, If sensor ranges/Td,Pc are known, disregard, validation
- Modify the model to account for these system differences.
  - o Instantiate the table below using the assessments from above. Note, this is a rough
  - o Note: When selecting a choosing individual factors it is sometimes possible for

Factor	Mission Attribute	Cal Modifier	Weight	Agent Attribute	Note	
Blue Agent Speed	30	-	-	30		From Step A3b (Mission)
Red Agent Speed	0	-	-	0		
Blue RoF	12	-	-	0		
Red RoF	26	-	-	0		
Blue Concealment	10	-	-	10		
Red Concealment	65	-	-	65		
Blue Ph (at 3500m)	0.150	-	-	0.150		
Red Ph (at 3500m)	0.400	0.263	0.70	0.326	Main Gun	
Blue Td (4000m)	8.000	-	-	8.000		New (Agent)
Red Td (4000m)	8.000	0.196	0.70	9.098	Veh	
Blue Pc (per det)	0.350	-	-	0.350		
Red Pc (per det)	0.350	0.196	0.80	0.295	Veh	

  - o Of these factors. Speed, RoF, Conc, and Ph have already been mission calibrated in the
- Transfer these factor settings and establish appropriate DOE ranges in the table below.
  - o The FR ranges will need to be adjusted to maintain the 40% to 95% victory calibration
  - o "Best" ranges (High or low), should be fixed based on the mission attributes above. I.e.,

	DPs	Factors	Low (40%)	Model	High (95%)
FR Attribute	1	# Blue Tanks	40	43	59
Mission Attribute	2	Red Ph (at 3500m)	0.326	0.350	0.400
Agent Attribute	3	Red Td	8	9	11
	4	Red Pc	0.295	0.325	0.350

The purpose of this step is to select and establish the range of Agent attributes that will be used to represent the impacts due to system level differences between weapon systems of the opposing forces. Simply speaking, these are the attributes that will be used to quantify the advantage of superior firepower within the model. To execute this step, the user begins by comparing the source data of the opposing forces system by system, and identifying the major areas where data support accurate comparison. For this example the source data for the IRCPAT included the comparison of systems in five

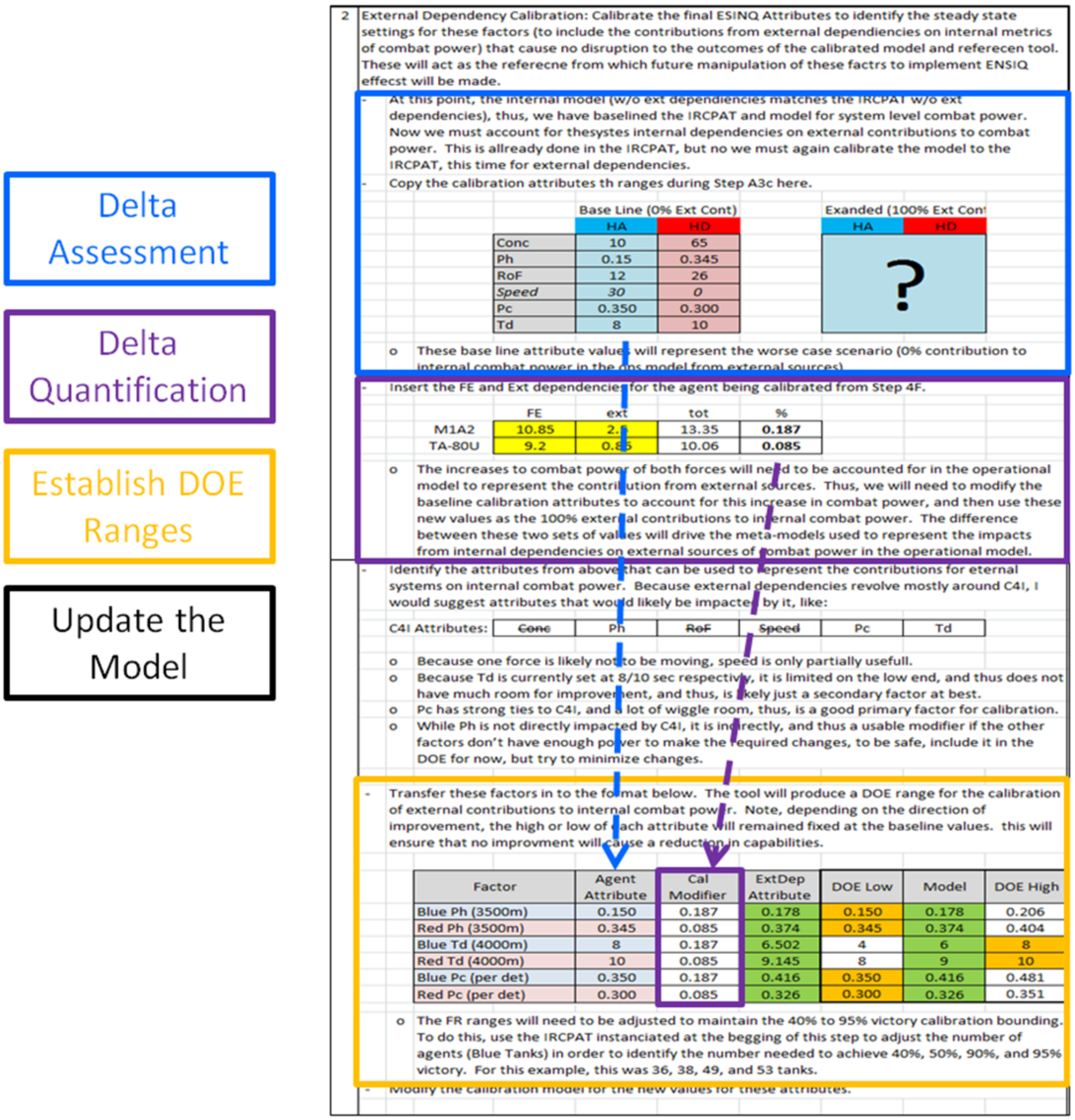
areas: system attributes, protection attributes, primary weapons attributes, secondary weapons attributes, and Command, Control, Communications, Computers, and Intelligence (C4I) attributes. Following the comparison, these differences were then assessed to determine if they were already being accounted for in the model, and if the difference was significant enough to demand calibration of the model. If the answer to both these questions was an affirmative, then calibration was deemed necessary. Of the 10 potential Agent factors identified during system comparison and assessment, only three were determined to require calibration, and included Red P_h, Red average Time between Detections (T_d), and Red Probability of Classification (P_c). The calibration of these three factors would be used to represent the system level differences between the opposing forces (tanks in this example). Of these three, P_h had already been accounted for during model calibration, thus, its value was simply updated. The other two Agent factors, T_d and P_c, had not been used previously, and therefore, require that both Red and Blue forces instantiate these Agent factors in the model. While both must be implemented within the model, the Blue Agent factors will remain fixed while the Red Agent factors are varied within the DOE.

Following this assessment, the user quantifies the impact from the system level differences, and calculates an estimated value for each of the Agent factors requiring calibration. For this example, the baseline factors settings from the model were modified by the % difference noted during assessment to achieve a modified version of each of the Agent factors, which now roughly takes into account the difference between systems. Please note, this is not a true quantification of Agent factors, but rather, it is just a rough estimate that only serves to inform the DOE which will follow. After the Agent factors are estimated, the potential range of these factors must be established. This is done similarly to before, with a mix of suggested ranges provided by the IMDP tools and subjective assessment by the user. While a broader DOE range will increase the exploration trade-space, it will also reduce the saturation of the solution space, thus requiring more M&S replications. Likewise, too narrow of a DOE window could limit the exploration space to a point that the user can risk not capturing a feasible Agent factor setting value. Thus, care must be made by the user when bounding DOE ranges. The last

step is to expand the model to account for these new factors, and to conduct a verification run to ensure that the model remains synchronized with the expanded reference tool. After the model verification, the model is ready for the DOE and analysis, which will account for the differences between opposing forces based on the specific systems used by both forces, and will be discussed in later. Following Agent calibration, the model can now be expanded yet again through ExtDep calibration.

The IMDP leads the user through ExtDep calibration by providing the user a set of generalized steps that allow for the identification of new ExtDep factors as well as modification of existing Mission and Agent factors to represent the agent internal dependencies on external systems. To do this, the IMDP provides a tool that directs the user through four general steps, which include: assessment of the agent differences; quantification of these differences; establishment of the DOE ranges for these ExtDep factors; and finally the expansion of the model. This process can be seen in Table 7.

Table 7. IMDP Part A3d: ExtDep Calibration



2 External Dependency Calibration: Calibrate the final ESINQ Attributes to identify the steady state settings for these factors (to include the contributions from external dependiencies on internal metrics of combat power) that cause no disruption to the outcomes of the calibrated model and referecen tool. These will act as the referecne from which future manipulation of these factrs to implement ENSIQ effecst will be made.

- At this point, the internal model (w/o ext dependiencies matches the IRCPAT w/o ext dependencies), thus, we have baselined the IRCPAT and model for system level combat power. Now we must account for thesystes internal dependencies on external contributions to combat power. This is allready done in the IRCPAT, but no we must again calibrate the model to the IRCPAT, this time for external dependencies.
- Copy the calibration attributes th ranges during Step A3c here.

	Base Line (0% Ext Cont)		Exanded (100% Ext Cont	
	HA	HD	HA	HD
Conc	10	65	?	
Ph	0.15	0.345		
RoF	12	26		
Speed	*30*	*0*		
Pc	0.350	0.300		
Td	8	10		

o These base line attribute values will represent the worse case scenario (0% contribution to internal combat power in the ops model from external sources)

- Insert the FE and Ext dependencies for the agent being calibrated from Step 4F.

	FE	ext	tot	%
M1A2	10.85	2.[illegible]	13.35	**0.187**
TA-80U	9.2	0.8[illegible]	10.06	**0.085**

o The increases to combat power of both forces will need to be accounted for in the operational model to represent the contribution from external sources. Thus, we will need to modify the baseline calibration attributes to account for this increase in combat power, and then use these new values as the 100% external contributions to internal combat power. The difference between these two sets of values will drive the meta-models used to represent the impacts from internal dependencies on external sources of combat power in the operational model.

- Identify the attributes from above that can be used to represent the contributions for eternal systems on internal combat power. Because external dependencies revolve mostly around C4I, I would suggest attributes that would likely be impacted by it, like:

C4I Attributes:	~~Conc~~	Ph	~~RoF~~	~~Speed~~	Pc	Td

o Because one force is likely not to be moving, speed is only partially usefull.
o Because Td is currently set at 8/10 sec respectivly, it is limited on the low end, and thus does not have much room for improvement, and thus, is likely just a secondary factor at best.
o Pc has strong ties to C4I, and a lot of wiggle room, thus, is a good primary factor for calibration.
o While Ph is not directly impacted by C4I, it is indirectly, and thus a usable modifier if the other factors don't have enough power to make the required changes, to be safe, include it in the DOE for now, but try to minimize changes.

- Transfer these factors in to the format below. The tool will produce a DOE range for the calibration of external contributions to internal combat power. Note, depending on the direction of improvement, the high or low of each attribute will remained fixed at the baseline values. this will ensure that no improvment will cause a reduction in capabilities.

Factor	Agent Attribute	Cal Modifier	ExtDep Attribute	DOE Low	Model	DOE High
Blue Ph (3500m)	0.150	0.187	0.178	0.150	0.178	0.206
Red Ph (3500m)	0.345	0.085	0.374	0.345	0.374	0.404
Blue Td (4000m)	8	0.187	6.502	4	6	8
Red Td (4000m)	10	0.085	9.145	8	9	10
Blue Pc (per det)	0.350	0.187	0.416	0.350	0.416	0.481
Red Pc (per det)	0.300	0.085	0.326	0.300	0.326	0.351

o The FR ranges will need to be adjusted to maintain the 40% to 95% victory calibration bounding. To do this, use the IRCPAT instanciated at the begging of this step to adjust the number of agents (Blue Tanks) in order to identify the number needed to achieve 40%, 50%, 90%, and 95% victory. For this example, this was 36, 38, 49, and 53 tanks.

- Modify the calibration model for the new values for these attributes.

The purpose of this step is to select and establish the range of ExtDep attributes that will be used to represent the impacts due to system dependencies on external systems for the generation of internal combat power. Simply speaking, these are the attributes that will be used to quantify the advantage of external dependencies within the model. To execute this step, the user begins by comparing the source data of the opposing forces system by system, and identifying the difference between opposing forces with regard to external dependencies. For this example the source data for the IRCPAT focused on the

comparison of C4I attributes. Following the assessment and comparison, these differences were then quantified, and potential surrogate factors for these differences inspected for relevance to the model. Of the six potential ExtDep factors identified during system comparison and assessment, only three were determined to be acceptable for potential use, and included Red P_h, T_d, and P_c. The calibration of these three factors would be used to represent the system level dependencies on external systems for the generation of internal combat power. Following this assessment, the user inputs the values in to the DOE tool to estimate the range of these ExtDep factors within the DOE. The last step is to expand the model to account for these new factors, and to conduct a verification run to ensure that the model remains synchronized with the expanded reference tool. After the model verification, the model is ready for the DOE and analysis, which will account for the differences between opposing forces based on the specific systems used by both forces, and will be discussed in later. Following ExtDep calibration, the model can now be expanded yet again through ESINQ calibration.

The IMDP leads the user through ESINQ calibration by providing the user a set of generalized steps that allow for the identification of new ESINQ factors as well as modification of existing Mission, Agent, and ExtDep factors to represent the impacts from the ESINQ factors of interest. To do this, the IMDP inserts the ESINQ factors identified and bounded in Step A1d (as well as the EEMM) into the calibration process by providing a simplified process that directs the user through four general steps, which include: ESINQ factor transfer; factor de-confliction; quantification of these differences; establishment of the DOE ranges for these ESINQ factors; and finally the expansion of the model. This process can be seen in Table 8.

Table 8. IMDP Part A3e: ESINQ Calibration

Transfer ESINQ Factors

1 ESINQ Calibration: Calibrate the ESINQ Attributes to identify the steady state settings for these factors that cause no disruption to the outcomes of the model and reference tool. These will act as the reference from which future manipulation of these factors to implement ENSIQ effects will be made in Part B.

- Copy the ESINQ Attributes identified from the EEMM Step A1c here. ** For demonstration reasons, I added in a few extra ESINQ effects to fully explain the process.

	Input Factor	Mission	Agent	ExtDep	Calibrate	Dependen
	Ave Det Time (sec)		Yes	Yes	No	Yes
	Prob Classification (%)		Yes	Yes	No	Yes
**	Latency (sec)				Yes	No
**	Reliability (%)				Yes	No
**	Ph per Discharge (%)	Yes	Yes		No	Yes

De-conflict Factors

- o Disregard any factors that have already been captured in mission, agent, or ExtDep calibration. In this example, this includes:

Mission Calibration:	Ph
Agent Calibration:	Ph, Td, Pc
ExtDep Calibration:	Td, Pc

- o Assess the system dependency on the ESINQ effect. For direct fire systems, with shooting based on Agent/squad SA, they can see the target and have limited dependencies on latency and reliability. For indirect systems, which shoot based on inorganic SA, are not as much effected by Td or Speed, but are heavily dependent on
- o If all ESINQ factors are accounted for in either Mission, Agent, or ExtDep calibration, or not necessary due to lack of dependency, this step is not necessary, all ESINQ factors have already been calibrated for steady state, and the user can move on to the
- o In this example, an M1A2 is a direct fire system, and thus, not sufficiently dependent on Latency or reliability, and thus, these factors would not need to be calibrated. To keep this demonstration moving forward, lets pretend we are looking at an indirect fire system instead. Thus, calibration of Latency and reliability would need to be

Establish DOE Ranges

- Transfer the remaining factors in to the format below. Unlike Mission, Agent, and ExtDep attributes, ESINQ attributes are currently fixed. The purpose here to simply include them into the model without impacting the output (assessing the baseline values for these ESINQ values). These values may or may not be mission/agent/ExtDep independent, and thus, the baseline values should not be assumed to be equal for both red and blue forces.

	Attribute	Range	DOE Low	Model	DOE High
Blue Latency (sec)	25	20%	20	25	30
Red Latency (sec)	20	20%	16	20	24
Blue Reliability (%)	99	5%	94	99	100
Red Reliability (%)	99	5%	90	95	100

- o Transfer the expected values from part A3a, then set a confidence range. This is an example, the values here are for demonstration purpose only.
- o Note: Because latency and reliability effect external squad communications, in this calibration model it will be applied too and from the links with higher HQ. In the example, this would not have any impact on the model, because as stated direct fire systems are not dependent on external comms. But to continue with the example, pretend that we were looking at artillery, who is dependent on external SA for targeting. The model would have included a source for that data, a HQ likely, and it is

Update the Model

- If no ESINQ factors need to be calibrated, there is no need to continue this step. If there is, the user would continue on as before, executing the following steps to conduct a DOE, analysis, and verification runs of the model to establish the baseline values of the ESINQ factors while ensuring that the model and the reference tool continue to remain

As shown in Table 8, the purpose here is to import the ESINQ factors (surrogates) that were identified in Step A1d, and establish the range of these factors that will ensure we can capture the steady-state value of each ESINQ factors during the DOE. Once calibrated, these values will serve as the baseline settings for each agent in the model, and provide a reference point from which future manipulation and trade-space explorations can be compared. This differs from the other calibration steps in a few ways. First, the steady state ESINQ factors are independent of the mission, agent, and ExtDep attributes

and thus, do not vary based as the others are changed. Second, while the other attributes will remain fixed in the model following calibration, the ESINQ attributes will not, and will be manipulated in order to demonstrate the impacts from the ESINQ factors. Thus, the ESINQ attributes calibrated here are intended to capture just the steady-state value, not the range of impacts due to the ESINQ factors; this will take place in part B.

This step starts with the inclusion of the five ESINQ factors identified during Step A1d and codified in the EEMM. Once imported, the surrogate factors that were previously addressed during Mission calibration were ignored, which for this example, included P_h, RoF, and Speed. Likewise, any surrogate factor that were addressed during Agent and ExtDep calibration were also ignored, which included Red T_d. This left just three unique ESINQ factors for inclusion, Blue T_d, as well as Red/Blue Latency (Lat). The ranges identified for these ESINQ factors in the EEMM are then transferred into the DOE format, establishing the ESINQ Attribute Ranges. The last step is to expand the model to account for these new factors, and to conduct a verification run to ensure that the model remains synchronized with the expanded reference tool. With the calibration steps complete, and the reference tool and model expanded to account for all three attribute types of interest, it is now time to move on to the next step, DOE, and produce the data necessary to support a thorough investigation of the trade-space.

Design of Experiments (DOE)

The third iterative step is the selection and build of the DOE to produce the required data necessary for a thorough exploration of the trade-space for each of the four attribute iterations. The purpose of the DOE is to provide an engineered approach to system experimentation specifically designed to produce data efficiently, across the entire system trade-space. As Beery (2016) mentions in his work, the “existing MBSE methodologies, as well as recent research in MBSE, fail to emphasize the importance of proper experimental design selection in the development of external models and simulations to support MBSE focused system development” (125). Through the proper use of DOE, it is possible for a user to efficiently explore the trade-space of a system, producing data of enough depth and detail to ensure that all significant interactions within the system as well as between the systems and the OE are identified.

The DOE step is identical for all four iterations, and does not change as we expand calibration to include Mission, Agent, ExtDep, and finally ESINQ factors. While the steps do not change, the focus of each DOE does. For Mission calibration, the purpose of the DOE is to capture the steady state values for the factors that will represent the impact of the specified Mission set on P_v. This DOE will likely have the most factors, as well as the broadest range of these factors, which will significantly increase the dimensionality of the solution space. Thus, this DOE will need to be large enough to ensure adequate saturation of the design space through techniques such as design stacking. For Agent calibration, the purpose of the DOE is to capture the steady state values for each Agent that will represent the impacts of systems specific capabilities on P_v. This DOE will focus on fine tuning known agent characteristics, and thus, will likely have fewer factors than Mission calibration as well as a much reduced range of these factors. This will reduce the size of the solution space, which will in turn reduce the size of the design needed to ensure adequate saturation of the design space. ExtDep calibration is very similar to Agent calibration, with the only difference being the factors selected to capture the steady state values for the external dependency of each Agent in the DOE. For ESINQ calibration, the purpose of the DOE is to capture the steady state values for each ESINQ factor of interest. Because the intent here is to establish a baseline value to serve as a reference point for future inclusion of ESINQ, and not to quantify the value, this DOE does not need to be nearly as detailed as the others. This detail will come later in the IMDP. Coupled with the fact that this DOE will not need to account for ESINQ factors previously calibrated, this DOE will likely have the fewest number of factors, which will again reduce the size of both the solution space as well as the design.

The importance of selecting an appropriate design cannot be overstated. The use of modern space-filling designs that ensure a thorough investigation of the trade-space as well as minimize the pairwise correlation of factors have vastly increased the understanding and insight gained from model exploration. As we saw with the use of non-optimal M&S packages, the use of non-optimal DOEs can be just as damaging to the development of an accurate understanding of the OE. Thus, users should use the most detailed design possible within the intent and constraints of the study. For more

information regarding DOE, to include a current catalog of modern designs, please refer to the NPS Simulations, Experiments, and Efficient Designs (SEED) Center for Data Farming website, at https://harvest.nps.edu/.

The DOE is executed for each of the four iterations to produce data of sufficient resolution to adequately inform the analysis process of each calibration step. The first of these iterations was for Mission calibration, which for this example included a combination of Force Ratio and Mission attributes, leading to nine total factors. Rather than selecting a nine factor 2nd order NOLH design as the IMDP would suggest, to save resources in this example, this work uses a much simpler NOLH design based on the work of Cioppa and Lucas (2007). The simpler design resulted in a much smaller design, just 33 DPs opposed to the 265 DPs required by a 2nd order NOLH design, and once stacked nine times and replicated 100 times, resulted in a 29,700 DP simulation run. While this simple design only guarantees near orthogonality for main effects, for this demonstration the loss in design resolution is well worth the reduction in complexity. The second of these iterations was for Agent calibration, which for this example included a combination of Force Ratio and Agent attributes, as well as one of the Mission attributes, resulting in a total of four factors. As before, a simpler NOLH design (seven factor) was used rather than selecting a four factor 2nd order NOLH design as the IMDP would suggest. After stacking and replication, the NOLH design resulted in an 11,900 DP simulation run. The third of these iterations was for ExtDep calibration, which for this example included a combination of Force Ratio, Mission, Agent, and ExtDep attributes, resulting in a total of seven factors. As before, a simpler seven factor NOLH design was used for a total of 11,900 DPs. The final DOE iteration was for ESINQ calibration, which for this example included a combination of Force Ratio and ESINQ attributes not captured in previous calibrations, which reduce the number of ESINQ factors from 10 to just four. Using the same designs from the Agent and ExtDep DOEs, this DOE resulted in an 11,900 DP simulation run. Following the development of the designs, they were uploaded to the NPS advanced computing cluster along with the model, and after the output data was returned, analysis was possible.

Analysis

The fourth and final iterative step in calibration is analysis, where the output data from each of the four DOE iterations is explored and analyzed to determine the steady-state factor values for Mission, Agent, ExtDep, and ESINQ factors. Like DOE, the analysis step is identical for all four interactions and does not change as we expand calibration to include Mission, Agent, ExtDep, and finally ESINQ factors. In fact, the only difference between the four iterations is the focus of the analysis, specifically the end-state. For Mission calibration, the end-state is to establish the baseline settings for the eight factors (P_{con}, P_h, RoF, and Speed, for both Blue and Red) that will represent the impacts of the selected Mission set on P_v. For Agent calibration, the end-state is to establish the baseline settings for the three factors (Red P_h, Red T_d, and Red P_c) that will represent the impacts from the assessed differences between the opposing weapon systems on the P_v. Similar to Agent calibration, ExtDep calibration will use Red P_h, T_d, and P_c to represent the impacts from the agent's internal dependencies on external systems to generate combat power in support of P_v. For ESINQ calibration, the end-state is to establish the baseline settings for the three factors (Blue T_d, Blue Lat, and Red Lat) that, in combination with the other seven ESINQ factors already accounted for, will represent the impacts from ESINQ factors of interest on the P_v. Analysis of the DOE results is executed for each of the four iterations to determine the attribute settings for the selected mission set within the model. These baseline settings will provide a set of factor settings that will capture the impacts of the selected Mission/Agent/ExtDep/ESINQ factors on the P_v within the model, calibrating the model output to the reference tool (+/-5%) across all Force Ratios. Additionally, the baseline ESINQ settings for each agent will also provide a reference point from which trade-space explorations can be analyzed in later steps to quantify the operational impacts from ESINQ factors.

This step starts with the Analysis and exploration of the DOE data. For this work, JMP was used to conduct the statistical analysis, regression, and contour profiling needed to determine the settings of the Mission, Agent, ExtDep, and ESINQ factors settings. The analysis began with a regression analysis to assess the significance of the individual factors, two-way interactions, and higher order interactions on the P_v. The regression was

then used as a screening tool to remove any insignificant factors. Following the regression, the contour profiler was used to explore the trade-space of the remainder of the factors, as demonstrated in the Mission Analysis example in Figure 49.

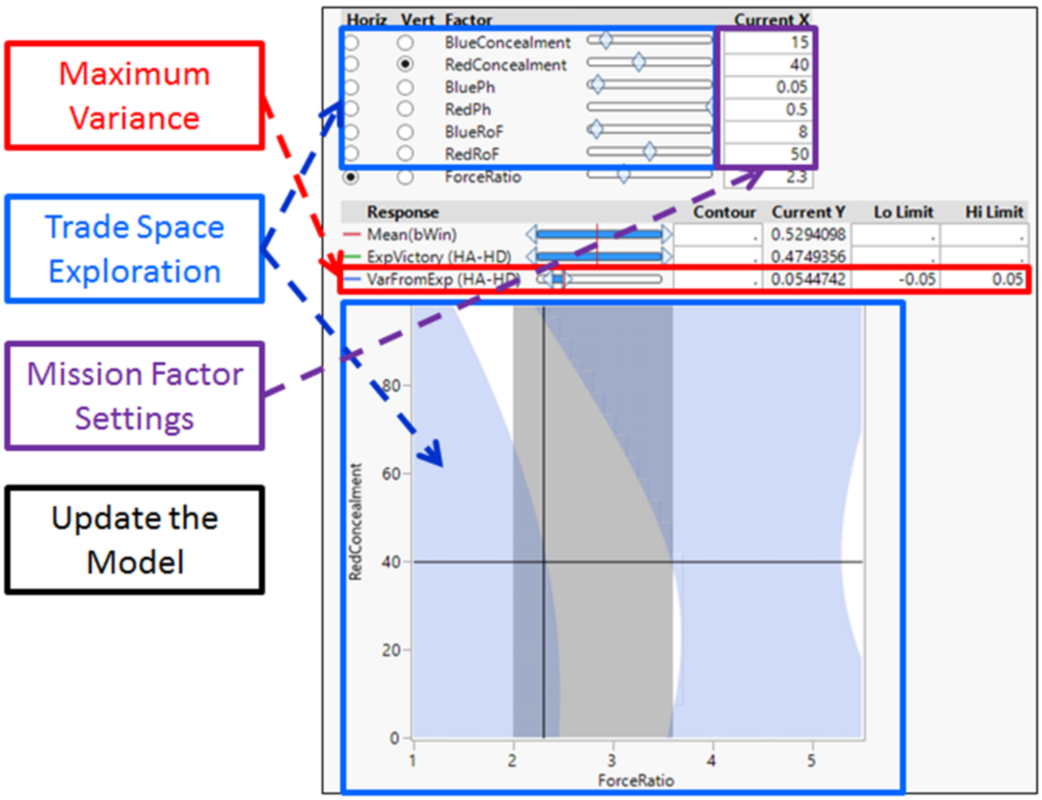


Figure 49. Contour Profiler from Mission Analysis

As shown in Figure 49, by setting the maximum variance between the model results and the expected results from the IRCPAT (victory curve #4) to +/-5% and then conducting TSE, a set of Mission factor settings were identified that ensured consistent results between the model and the reference tool, as indicated by the range of feasibility (white area) across Force Ratios of 2.3 to 3.65. While these settings do not cover the full calibration range of 2.0 to 3.65, the fact that the deviation is on the low side of P_v, from roughly 25% to 45% P_v, most users would be willing to overlook it because any solution in this range would likely be considered unacceptable. These factor settings capture the Mission specific advantages of the defending force, and are recorded for future use.

These factors will be used to update the model prior to the Agent, ExtDep, and ESINQ calibration iterations, and following the completion of all four calibration iterations, will be used in the development of the complete model. With factor settings recorded, the next step is to verify the results by executing a one factor DOE, where we vary just the Force Ratio (#Blue Tanks) to verify that the output of the model mirrors the expected results shown by the reference tool across the full range of potential FRs. The results of this analysis can be seen in Figure 50.

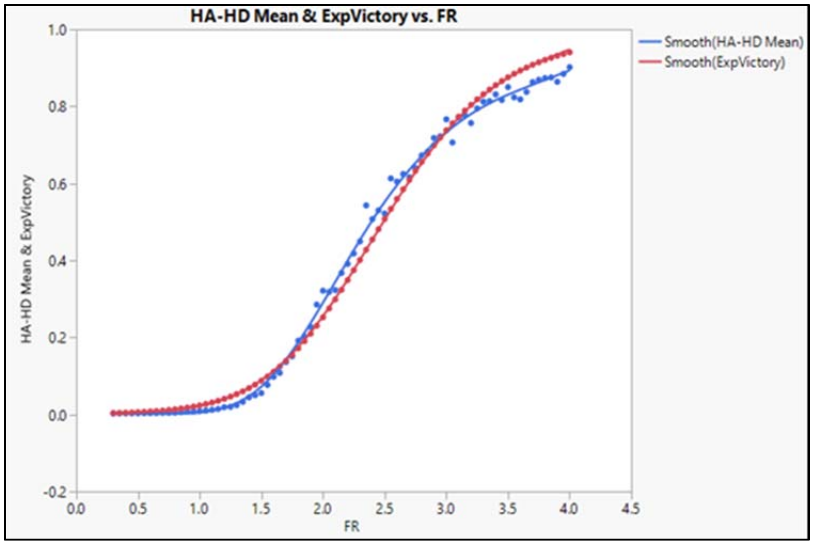


Figure 50. Analysis Verification: Mission/Agent/ExtDep Attributes

The verification DOE confirmed that the Mission factor settings identified through the calibration iterations produced nearly identical results between both the model and the reference tool when implemented. Thus, the model is Mission calibrated with the reference tool and capable of producing results that fall within +/- 5% of the reference tool across all FRs. Following mission calibration, the expansion of the model, and recording of the Mission settings, the calibration process described in this section is repeated for Agent, ExtDep, and ESINQ factors during their specific calibration iterations. During these iterations, the Mission analysis results, which captures the model factor settings, are iteratively modified and expanded to capture Agent, ExtDep, and

ESINQ baseline factor settings for the model. The complete calibration verification can be seen in Figure 51.

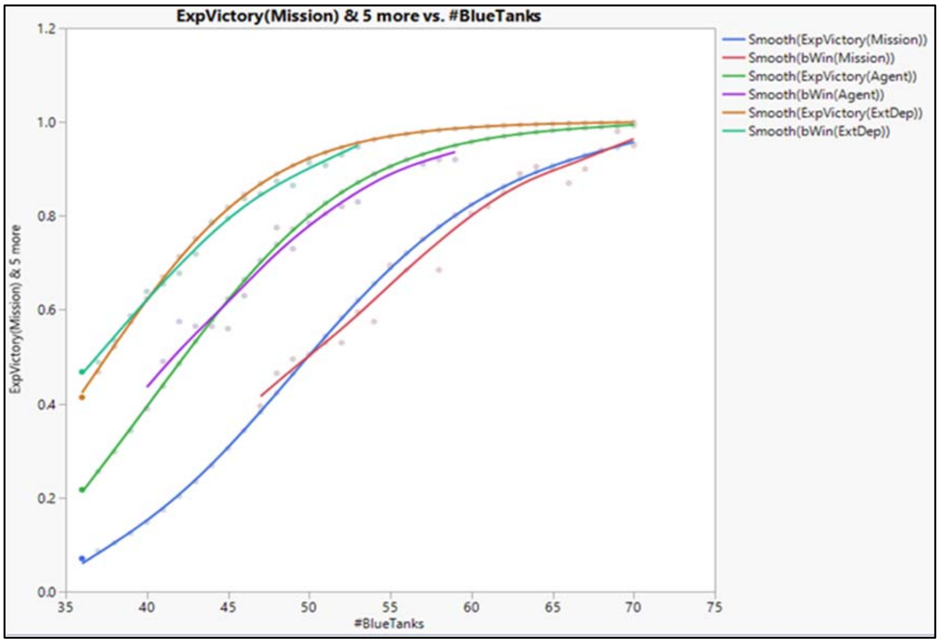


Figure 51. Mission, Agent, ExtDep Calibration Results

As shown in Figure 51, as the model was expanded to capture a more accurate representation of the OE, the RCP of the Blue force increased, which required a reduction in the number of Blue Tanks to maintain the same P_v range (40%-95%). The end state of part A is a calibrated set of Mission, Agent, ExtDep, and ESINQ attributes that accurately link the reference tool to the model. When introduced into the model, these attributes will enforce consistent outcomes between the reference tool and the model, across all potential mission sets and FRs. At this point, these attributes are ready for inclusion into the final model and will provide a stable reference point for the assessment of ESINQ effects on metrics of combat effectiveness.

b. *Part B: Model Development*

Part B of the IMDP expands the capabilities of current MDPs and MBSE analysis methodologies by providing users an improved methodology for producing more accurate

models utilizing the calibrated data from part A. The purpose of model development is to finalize the implementation of the simplified model as envisioned in the OC, and then to expand that model to highlight the impacts that ESINQ factors can have on metrics of operational effectiveness. As described in Figure 52, part B has two primary steps.

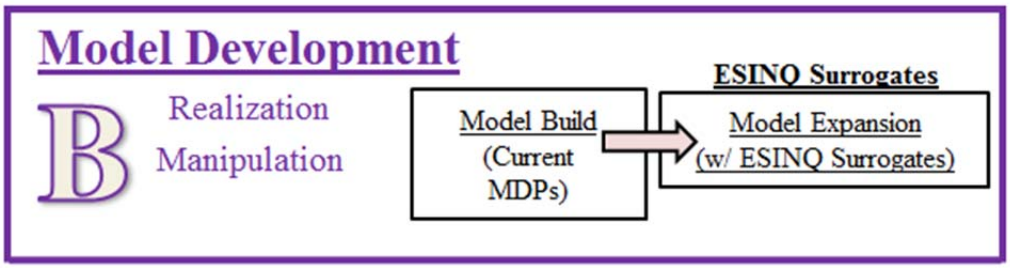


Figure 52. IMDP (Part B)

By providing a means for models to account for ESINQ factors, the models can capture a more accurate understanding of the OE. Part B of the IMDP does this through the formalized realization and manipulation of the model, with the goal of improving the overall utility of the model by increasing the accuracy of the supporting data. A more detailed description of part B can be seen in Table 9.

Table 9. IMDP: Part B

Part B	1a	Develope the model to improve its capacity to meet user needs and requirements, without any modification to the ESINQ factor surrogates from Mission/Agent/ExtDep/ESINQ calibration identified in Part A. This is an iterative process where you build model capacity by adding in other modeling aspects ignored during calbration, like other forces. Conduct analysis as needed to adjust and fine tune the model. 1000 Iterations of the model should be calibrated to within (+/- 5%) of the output from the IRCPAT. To verify, execute a 1 x factor DOE to establish a analysis reference point for future comparison.	Realization
	2a	Expand the model to include the ESINQ factors identified in Part A by modify the ESINQ factors from their baseline values to a setting which achieves the expected impacts from each ESINQ effect. This task supports the development of operational support tools.	Manipulation
	2b	Execute a full 2^{nd} Order NOLH DOE across all Force Ratios to establish a new analysis reference point, used to quantify the operational impacts from the ESINQ effects of interest across all full range of severity. Same DOE process as described in Part A3b-e.	
	2c	Quantifying ESINQ Effects: Data analysis and Meta-model development for the responses of the ESINQ factors, quantifying operational impacts. Same Analysis process as described in Part A3b-e.	

Both realization and manipulation can be broken down further into lower level processes, but as before, these lower level processes and their associated products will not be discussed in depth here, but will be defined and demonstrated in Chapter IV. The intent of this section is to provide the reader more detail regarding the conceptual flow described in Figure 46, specifically the functions of realization and manipulation.

(1) B1: Realization

As described in Table 9, the purpose of realization is to finalize the model build as described in the OC, based on the users' needs, requirements for the study, the selected mission set, without any modification to the ESINQ factors or surrogates. Realization focuses on improving the simplified model used in part A through the addition of all remaining elements of the model, to include other forces that were ignored during calibration. At the conclusion of this step the complete model will be constructed, and it will be synchronized with the reference tool and ready for expansion to account for the impacts from ESINQ factors if interest.

B1a: Model Development

Fortunately, the majority of model development has already been completed, resulting in a fairly simplified development process when compared to the development of the model in part A3a, and thus, this step will not be discussed in detail, although it will be demonstrated in the next chapter. At this point, all aspects of the model that were identified as requirements in the OC should have already been implemented in the model, though they may not all be active yet. Thus, there are only some small modifications necessary to implement the aspects of the full model that were ignored in part A due to directives of the IMDP. For the most part, these aspects deal with the addition of other forces not calibrated during part A. During this step, each of these additional forces is integrated into the model through an implicit calibration technique described in the IMDP. This is a "partial" calibration from those conducted during part A, and because our baseline calibration focused on the most significant system/s, it is possible to add additional forces to the model at relatively low resolution while maintain synchronization with the IRCPAT by modifying just a few select factors of each agent type. The IMDP

directs the implicit calibration of these agents through the execution of a DOE, where the DOE ranges are based on the respective percentage of contribution to the overall RCP of each agent. Following model development and implicit calibration, verification of the model is conducted to enforce linkages with the reference tool. To do this, the model is replicated 1000 times to verify that the model is still calibrated to within (+/- 5%) of the output from the operation reference tool (the IRCPAT) developed in the previous step. Then, a one factor DOE is executed to capture the impacts of changing Force Ratio on P_v. The purpose of this verification is to set the conditions for the future expansion of the model to account for the impacts of the ESINQ factors of interest, as well as to collect summary statistics to serve as a reference point for the quantification of ESINQ impacts.

(2) B2: Manipulation

Manipulation focuses on expanding the model to account for the impacts of the ESINQ effects and then, through comparison of the model outcomes (Manipulation), to quantify the effects of the ESINQ factors on metrics of combat effectiveness, which is the end state of the IMDP. Once the model is verified and analysis complete, the model is then expanded to include the users expected impacts from the ESINQ factors of interest. Following the development of the model, the results of the reference tool and the model will begin to deviate, based on the impacts that the ESINQ factors and their effects had on the model. It is this deviation in which we are interested in, and by measuring it will provide the quantifiable assessment of the impacts of the ESINQ factors on metrics of operational effectiveness. This is done in a manner similar to the process of calibration described in part A, where we systematically expand the model, execute a DOE, and then conduct analysis to capture the impacts. Following these steps, we use the resulting meta-models to inform the reference tool, and thus, re-linking it to the model. This expansion of the calibration process discussed in Figure 47 can be seen in Figure 53.

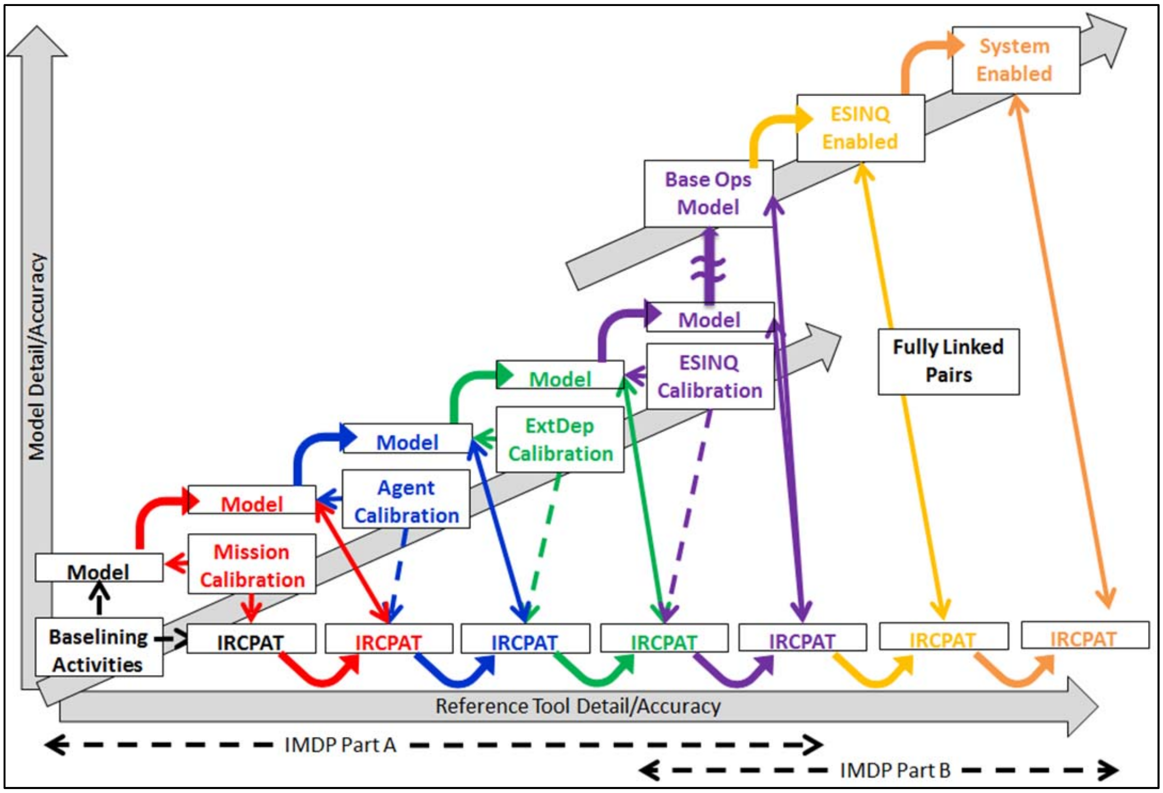


Figure 53. Model Development Expansion of Calibration

As shown in Figure 53, the Mission, Agent, ExtDep, and ESINQ factor settings determined during part A are used to develop the model in part B, which will capture a much more realistic representation of the OE than the model used during calibration. Once the model is developed, an iterative process is used to expand the model as needed by the user. For this work, this included the expansion of the model to include the ESINQ factors of interest, and following DOE and detailed statistical analysis of the generated data, meta-models can be generated to serve as surrogates for the model. These meta-models can then in turn be used to support the understanding of the systems within the OE, including the impacts from ESINQ factors. The use for these meta-models is nearly limitless, and when used in conjunction with other tools, can provide a more refined understanding of the system within the OE. Manipulation has three primary steps: expansion of the model to account for ESINQ effects; DOE selection and execution; and analysis and meta-model development.

B2a. Expansion of the Model

The purpose of this step is to expand the model to account for the ESINQ effects of interest identified during part A of the IMDP. While this is a fairly straight forward process, requiring only minimal modifications to the model, care must be taken in how these modifications are made to ensure this process provides more than a subjective assessment. This step of the IMDP guides the user through the formalized bounding of ESINQ impacts using a value based process that is informed by quantifiable source data. This four step process helps the user better assess and visualize the expected impacts from the EISNQ factors of interest. While this impact assessment can be subjective, it is more informative if based on data from qualified sources, and thus, should be based to the largest extent possible on quantifiable sources of impact data. While this may prove difficult, a user who can successfully integrate both the art and science of the MDP, as seen in military decision making, will have a much higher likelihood of capturing a more accurate range of impacts. For this work, the expected impacts based on the SMDC assessments of threats and capabilities described in Chapter II and Appendix B were used. The ESINQ impact assessment for an example problem can be seen in Table 10.

Table 10. IMDP B2a-1-2: Initial ESINQ Response Bounding

User ESINQ Impact Assessment

Visualization Tools

Bounding ESINQ Impacts

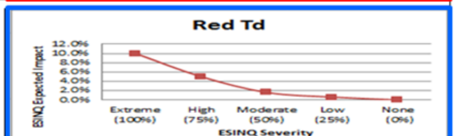
Establish DOE Factor Ranges

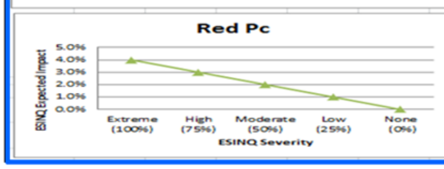
1 Initial ESINQ Response Assessment.

- Import the linked input factors from part A1c/EEMM into column 1 for the 1st ESINQ factor of interest.
- Identify the number of levels of severity you want to represent, more is better, and will yield a better representation of the expected response, but for simple curves, it may not bee needed. This data will drive the creation of response meta-models used for instantiating the DOE. Create a Column for each of these, for this example, I used just 5 levels of severity as seen in Column 2.
- Input expected impact (% change from base value) based on severity for each of the linked input factors into column 2. This should be informed to the largest extent possible by quantifiable sources of impact data. The key is to assess as accurately as possible the expected form, or shape of the response curve. Typically, the form of the curve is better understood than the quantifiable impacts, which is why we start here. The scaling of these curves will come later during bounding. Use the value curves to help support the impact assessment (the curve). This should be assessed by as many SME as possible, leading to an outcome that is acceptable by most.

1	2				
Linked Input Factors	ESINQ Factor Severity (Degraded ISR)				
	Extreme (100%)	High (75%)	Moderate (50%)	Low (25%)	None (0%)
Ave Time/Det	10.0%	5.0%	1.6%	0.6%	0%
Pc	4.0%	3.0%	2.0%	1.0%	0%

  - o Because this demonstration was looking at the impact of degraded ISR on Blue tanks, in a small protracted fight, the immediate impacts on the force will be relatively small. Thus, the degradation to combat effectiveness is likely small. For other forces, or with other ESINQ factors, these curves could be quite different. it is for this reason that these curves should be done for each agent-ESINQ combination.





2 Bounding the Response

- Because the user will likely only have a basic approximation of the expected impacts from ESINQ factors...which is why they are ESINQ, an investigation into the power of the response to impact operational effectiveness is needed to bound the response to a region of feasibility. Using the values from above is extremely subjective, a best guess, and would likely induce more variability into the model outcomes than would be desired. This step helps refine the estimation of factor settings by bounding them through DOE.
- First select a base ESINQ impact value for each factor. To do this, make an assessment of the likely maximum % impact that the ESINQ effect would have compared to the contributions from External dependencies. This grounds the assessment of ESINQ impacts on something that has already been accounted for and calibrated in the model.
  - o For this example, I assess that the maximum of degraded ISR to be roughly 20% of the impacts from external dependencies seen in part A3d, which was captured in the following factors settings:

0% Contribution		100% Contribution		Delta	
Red Pc	Red Td	Red Pc	Red Td	Red Pc	Red Td
0.300	10	0.230	12	-0.070	2.000

Maximum Impact	0.20

  - o Thus, the maximum expected impact from ESINQ effects is:

Estimated Impact	
Red Pc	Red Td
-0.014	0.400

- Import the baseline ESINQ factor settings from part A3d, to include the modification to account for 100% external dependencies. Import just the ESINQ effects identified in A1c/EEMM, using the values from part A3d. Recall, a degradation to Blue forces in this example is shown through a improvement to Red capabilities.

	Imported		Modified	
	HA	HD	HA	HD
Pc	0.350	0.230		0.244
Td	8	12		11.600

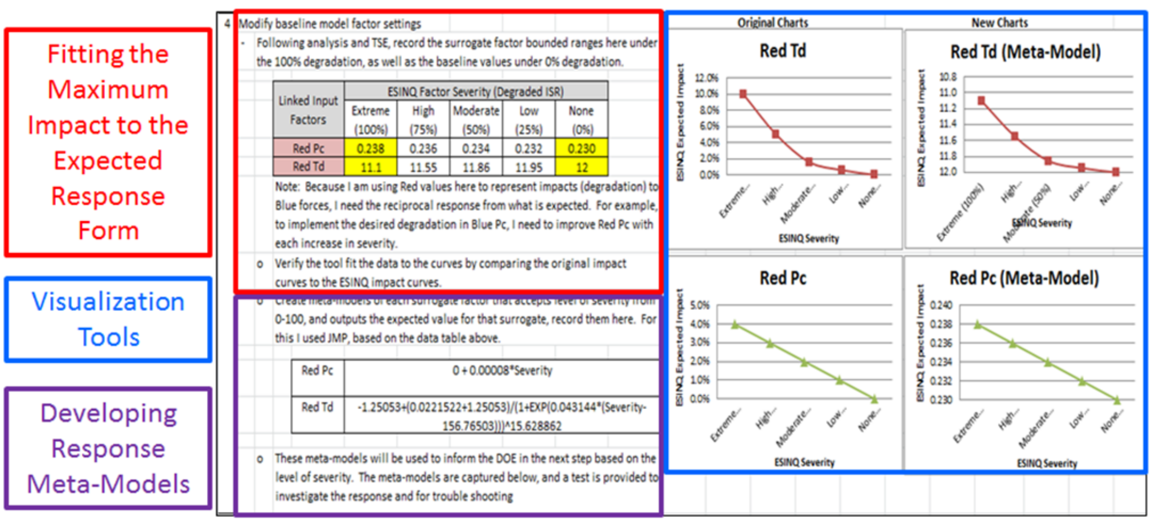
- Build a multifactor DOE across the range of impacts established above, using the FR range from B1a. Round where necessary in the direction of an expanded range. For a better model fit, apply the range to both sides of the base value, failure to do this risks a flawed fit which can induce anomalies into data analysis.

DPs	Factors	Low	Base	High
1	# Blue Tanks	37	42	56
2	Red Td (sec)	11.0	12.0	13.0
3	Red Pc	0.216	0.230	0.244

As shown in Table 10, the first two steps of the model expansion directs the user through a somewhat subjective, yet informed process that supports the estimation of ESINQ impacts of model factors identified in previous steps. The key to this step is to supplement this assessment with quantifiable support data that justifies the impact assessments made here. The more data you have supporting the impacts assessments made here, the more accurate the model will be in representing the ESINQ factors of interest. Thus, depending on the user as well as the data available, this assessment can span the range from purely quantitative, which is unlikely due to the classification of these factors as ESINQ, to purely subjective, with is far less desirable. Even if no data is available, the use of SMEs can greatly aid in these assessments, and should be used whenever possible. Next, because the user will likely only have a basic approximation of the expected impacts from ESINQ factors, an investigation into the power of the response to impact operational effectiveness is needed to bound the response to a region of feasibility. Using the values from the initial assessment can be extremely subjective, and

potentially induce more variability into the model outcomes than would be desired. By bounding the response to the model, specifically the impacts from external dependencies which were previously calibrated, and then establishing a maximum impact of those effects with respect to external dependencies, we can further refine and bound the estimated response range. Then, through the use of a small multi-factor DOE, we can explore this estimated ESINQ response region and identify the ESINQ surrogate factor settings that produce the maximum expected impact while minimizing variability. Finally, using this calibrated maximum effect, fit it to the value curve developed earlier, and build a representative meta-model of the expected response. This final step, following the DOE and analysis can be seen in Table 11.

Table 11. IMDP B2a-4: ESINQ Response Meta-Model Development



The meta-models developed in this step will calculate the factor settings for each ESINQ surrogate factor based on the expected level of ESINQ severity, bounded by the estimated and calibrated response range established in the previous steps. If desired, these meta-models can be used to expand the model by including the impacts from the ESINQ factors of interest, bounded by the impact ranges selected in Table 10. This expansion requires the modification of pre-existing factor settings to act as surrogate factors for the ESINQ factors of interest. Following analysis, this should provide the user the expected

impacts to combat effectiveness from the ESINQ effects for the specified mission set and task organization modeled.

B2b: DOE Development and Execution

This step focuses with the selection, design, and execution of the ESINQ impact DOE, which will determine the richness of the interactions between the ESINQ effects on the outcomes of the model. This step will follow the same general process as the DOEs conducted in part A: calibration, with the two major exceptions being that the factors being manipulated here are the EISNQ factors of interest bounded during the previous step, and the methods in which the design is built. This process has five general steps as described in the IMDP. The first step requires the building of the base design, which will include just two of the four total factors, the FR factor (#BlueTanks) and the severity factor. A larger than necessary design is typically preferable to ensure saturation, and should be used when possible. For this four factor design, a seven factor 2nd order NOLH with 125 DPs would have been recommended. Next, if more saturation of the solution space/design space is needed, the user can choose to stack the design. For this example, the design would have been stacked seven times; resulting in an 875 DP design. Following the instantiation and stacking of the design, it is then expanded to include the remaining two surrogate factors (Red T_d and P_c),which have their factor settings calculated based on the level of severity at each DP using the meta-models developed in part B2a. Next, the design is scoped, where the design is formatted in preparation for its execution by the model. This is model specific, and may require scaling, translation, and other modification to the input data. Finally, after replicating each DP, 400 times in this example, the design resulted in a 350,000 DP simulation run, which was executed on the NPS advanced computing cluster. Once the output data was returned, it was possible to conduct analysis to quantify the impacts from ESINQ factors on the model.

B2c: Analysis and Meta-Model Development

Once the DOE data is generated, it is then analyzed with the purpose of establish a mathematical representation (meta-model) of the operational impacts from the ESINQ factors of interest on the primary metrics for combat effectiveness, namely P_v, LER, and

FER. Recall, that the contribution of this work is to provide the means (the IMDP) to create an ESINQ enable model, which was technically complete following part B2a. At this point we are simply trying to quantify that impact in terms of a meta-model that can be used to better inform decision makers as well as for future use in other support tools. To do this, a meta-model is developed of the ESINQ factor response on the model (P_v), across all potential FRs and each level of ESINQ impact severity identified by the user. This is done in the same manner described previously, and simply requires regression and statistical analysis using JMP. The meta-models generated through this process, while not linked to the system of interest yet (Chapter V), can mathematically quantify the impacts of these ESINQ factors of interest on the model. By developing individual meta-models now, that tie individual ESINQ impacts to metrics of operational effectiveness, we can set the conditions for the future application of the IMDP outcomes in support of operational and acquisitions planning. This is useful when considering the inability of most tools to account for ESINQ effects, to include the reference tool used in this work. Because we enforcing the calibration and linkage of the model and reference tool throughout the execution of the IMDP, it is possible to take this meta-model and use it to expand the reference tool to allow it to account for ESINQ effects, which is one of the secondary contributions of this work. And while the expansion of external tools is an application, and technically outside of the scope of the IMDP and this work, it will be discussed in Chapter V, specifically with regard to the expansion of the IRCPAT and acquisitions TSE.

The end state of part B of the IMDP is the development of a set of meta-models that can accurately represent the impacts of the ESINQ effects of interest on metrics of combat effectiveness measured from inside the model. These meta-models are the key to expanding current operational and acquisition decision support tools, and will enable a more complete understanding of the system and the OE, which presents some significant advantages for users. First and foremost, it allows users to quantify the impacts from ESINQ effects, which are often ignored in traditional MDPs. Second, it encourages users to apply that knowledge to other tools to improve their accuracy. By following the IMDP, the user can ensure better synchronization between the modeled environment and the

actual OE, improving the overall MDP referent while providing traceability back to the originating requirements. Additionally, the IMDP supports some level of validation of the resulting outcomes through calibration with a reference tool.

4. Summary

The purpose of this chapter was to describe the IMDP and how it expands current MDPs and MBSE Analysis Methodologies to more accurately account for ESINQ factors within a model. The overarching goal of this work is to improve the decision-making process of leaders in both the operational and acquisitions communities by providing a more robust analysis methodology that can be leveraged to develop more accurate decision support tools. The IMDP described in this chapter provides analysts the means to simultaneously evaluate an emerging system's performance across all four referents of D3SOE mitigation. Specifically, the IMDP will allow for the more accurate representation of ESINQ factors by bounding their response ranges within models. The IMDP presented in this work provides users the ability to loosely quantify or "bound" the impacts from ESINQ factors on operational effectiveness, and facilitates a more complete understanding of a system's performance with respect to the OE. Additionally, this work supports the development of a range of new and improved operational and acquisitions decision support tools that can more accurately account for the impacts of not only the effects internal to the system boundary, but also the ESINQ effects on the system. By following the IMDP presented here, a better evaluation of the OE can be made, which will allow for more informed operational and acquisition decisions regarding the allocation of resources. A description of how this work expands the current body of knowledge can be seen in Figure 54.

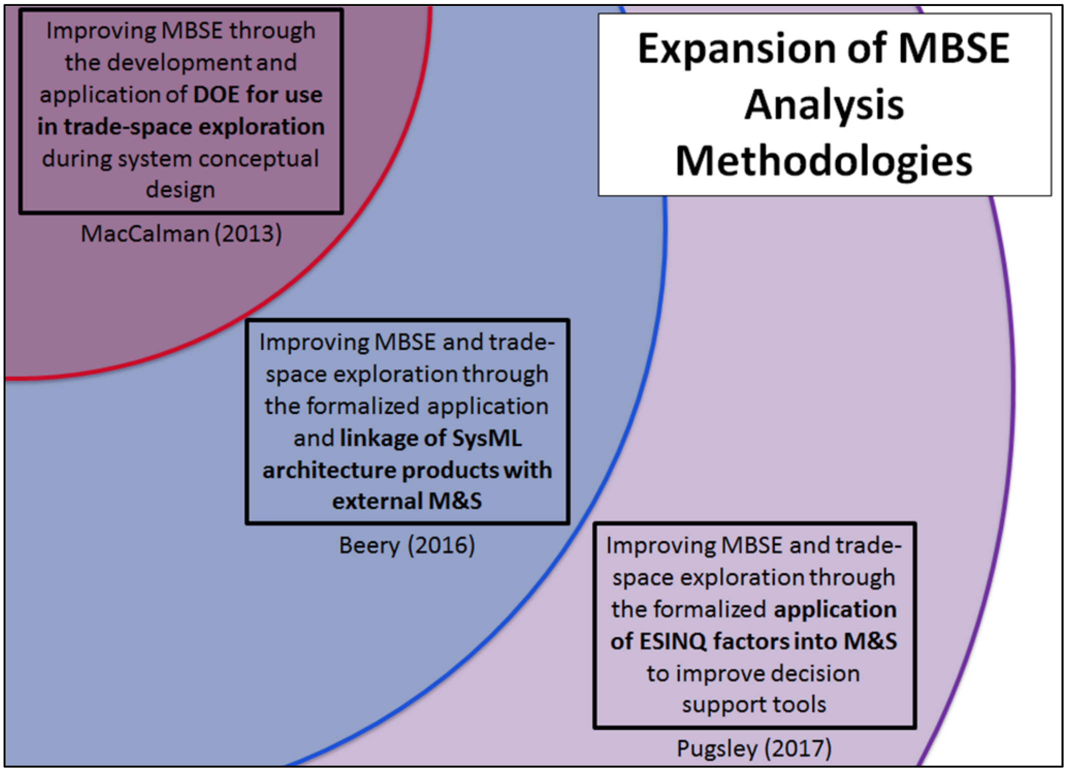


Figure 54. Expansion of MBSE Methodologies.
Adapted from Beery (2016) and MacCalman (2013).

As shown in Figure 54, this dissertation expands the TSE work of both MacCalman and Beery and provides a formal methodology for developing ESINQ enable models, which can provide more robust models, that capture a more accurate representation of the OE. Once used in conjunction with MDPs and MBSE analysis methodologies, this expanded model could provide a more detailed description of the system and support a better investigation of the system trade-space. With the description of the IMDP complete, we will now move on to providing a more detailed demonstration of the complete process using a more current and impactful problem, specifically tied to the author's research interests in ground combat operations in a D3SOE.

IV. IMDP DEMONSTRATION

To highlight the utility of this work, this chapter presents a fully executed IMDP to provide context and articulate in greater detail the IMDP described in the previous chapter. While the mock scenario and models used in this chapter will all be fairly simple, the associated products of the IMDP and the outcomes described here will fully demonstrate the overall applicability of the IMDP to quantify the impacts of ESINQ effects of interest. The quantification of these ESINQ factors, and the application of this knowledge to improved decision making are the root of this work, filling known gaps and expanding the current body of knowledge with regard to MDPs. To demonstrate this process, this chapter will begin with a description of the scenario, which includes a need statement that will drive the IMDP. While simplistic, this mock scenario will provide the foundation for the execution of the IMDP that will comprise the majority of this chapter. The end state of this chapter will be the quantification of the ESINQ factor and effect of interest and its codification through the use of meta-models.

A. THE SCENARIO

One of the key enablers to modern operations is the use of UAVs to supplement ISR collection activities. Unfortunately, while UAVs have provided immense value to the Army, they often lack access, adequate range, and survivability in large-scale conflict, especially when considering the threats posed by China and Russia. To mitigate potential risks, the Army has been considering the procurement of SmallSat ISR collection platforms to expand its collection capacity to other domains like space. Unfortunately, before accurate assessments of the overall utility of these systems can be made, the dependency of the ground force on space-based collection assets as well as their vulnerability to degradation from adversary counter-space activities must be understood. With these considerations in mind, the following operational need was used to drive the IMDP demonstrated in this chapter.

The Army is interested in accessing the potential impacts to combat operations from adversary degradation of space-based ISR assets. As an introductory exploration of

this topic, the Army wants to look at the impacts this degradation can have on a typical Armor engagement between the M1A2 Main Battle Tank and a near peer equivalent, like the T-80U. To maintain consistency with the threats, mission sets, and the expected OE outlined in the AOC, the Army wants to focus on operations at the BN/BDE level of warfare, specifically short period engagements where U.S. forces are attacking defended positions and at a distinct disadvantage from the adversary forces. Specifically, the Army is interested in determining how much more force structure (number of tanks) would be needed to overcome the adversary's counter-space activities.

By quantifying the dependency of ground forces on space-based ISR assets in terms of their contributions to RCP, it will be possible to better understand the OE and thus, make better decisions regarding the allocation of resources. This improved understanding could provide operational planners with a more accurate assessment of adversary counter-space activities, allowing them to more accurately assess the number of tanks needed to achieve a desired end state. Likewise, this improved understanding could better support acquisitions by providing quantifiable impact data, enabling decision makers to make more informed decisions regarding the utility of competing systems with respect to the systems contributions to RCP. It is this overall need that will drive the IMDP demonstrated in this chapter.

B. THE IMDP

The overall goal of the IMDP is to improve the overall accuracy of the model through the directed manipulation of the supporting data. To do this, the IMDP expands the capabilities of current MDPs and MBSE analysis methodologies by formalizing the process for bounding ESINQ effects in a manner that more accurately translates to models, thus increasing the accuracy of the model without increasing its complexity. The IMDP does so through the formalized translation, normalization, and calibration of modeling input factors to develop a more complete understanding of the OE. Once this improved understanding is gained, the part B of the IMDP transfers this improved understanding to the model through a formalized process of realization and manipulation. A detailed description of the complete IMDP can be seen in Table 12.

Table 12. IMDP

Part	Phase	Step	Description
Part A	Translation	1a	List and describe the primary external, and seemingly intangible and non-quantifiable effects in which you are trying to represent. (Use EEMM)
		1b	Identify and list the tangible impacts on combat operations which the effects in Step A would likely have. (Update EEMM)
		1c	Using the MSSSM, investigate potential Combat Models and identify a Model with appropriate factors which can best model the tangible impacts from Step 4B, that can be used as surrogates for the intangible effects. For the rest of this methodology I will be using MANA as my M&S package. (Update EEMM)
	Normalization	2a	Selection of a reference tool
		2b	Base Line the Force Analysis System Weights Spread sheets to account for C4I contributions to combat power, then break this contribution into both external and internal contributions (If using the Improved Relative Combat Power Assessment Tool (IRCPAT), skip this step, this has already been done.
	Calibration	3a	Baseline Calibration. Build a simplified model and instantiate the reference tool.
		3b	Calibrate the "Mission Attributes" to establish the baseline mission specific attributes for each agent for the selected model and mission set.
		3c	Calibrate the "Agent Attributes" for each agent to account for variations in capabilities based on the Improved Force Analysis System Weights Spread sheets to create the final "Agent Attributes" to be used in the Model.
		3d	Calibrate the "External Dependency Attributes" for each agent to account for internal dependencies on external sources for the generation of internal combat power to create the final "ExtDep Attributes" to be used in the Model.
		3e	Calibrate the "ESINQ Attributes" to establish the baseline ESINQ specific attributes for each agent for the model.
Part B	Realization	1a	Develope the model to improve its capacity to meet user needs and requirements, without any modification to the ESINQ factor surrogates from Mission/Agent/ExtDep/ESINQ calibration identified in Part A. This is an iterative process where you build model capacity by adding in other modeling aspects ignored during calbration, like other forces. Conduct analysis as needed to adjust and fine tune the model. 1000 Iterations of the model should be calibrated to within (+/- 5%) of the output from the IRCPAT. To verify, execute a 1 x factor DOE to establish a analysis reference point for future comparison.
	Manipulation	2a	Expand the model to include the ESINQ factors identified in Part A by modify the ESINQ factors from their baseline values to a setting which achieves the expected impacts from each ESINQ effect. This task supports the development of operational support tools.
		2b	Execute a full 2^{nd} Order NOLH DOE across all Force Ratios to establish a new analysis reference point, used to quantify the operational impacts from the ESINQ effects of interest across all full range of severity. Same DOE process as described in Part A3b-e.
		2c	Quantifying ESINQ Effects: Data analysis and Meta-model development for the responses of the ESINQ factors, quantifying operational impacts. Same Analysis process as described in Part A3b-e.

Using the scenario and the associated need statements from the previous section, this section will execute the full IMDP, from start to finish, to demonstrate the utility of the process to bound ESINQ effects of interest. To minimize any repetition with previous chapters, this chapter is presented in a manner which can best replicate the execution of the process from the user's perspective. It is assumed that the reader has a general understanding of the IMDP as outlined in Chapter III and can follow along with the logic presented here. Thus, this chapter will forgo the majority of definition and focus on demonstrating the development of the IMDP outcomes necessary to progress the user through the IMDP and toward the quantification of his/her ESINQ factor/effect of

interest. Because the IMDP was developed with the user in mind, it is difficult to demonstrate passively, thus, this chapter will be presented from the first person view to provide a more realistic demonstration. While the first person is more informal than typically desired, it will provide the necessary context to fully articulate the IMDP.

1. Part A: Model Definition

Part A of the IMDP expands the capabilities of current MDPs and MBSE analysis methodologies by formalizing the process for bounding ESINQ effects in a manner which more accurately translates to models than traditional MDPs allow, thus increasing the capacity of the model to capture a more accurate representation of the OE without increasing the models complexity. The IMDP does this through the formalized translation, normalization, and calibration of modeling input factors with the goal of improving the overall accuracy of the model through a directed manipulation of the supporting data. These 10 sub parts, executed to address the scenario described at the begging of this chapter, will now be described.

a. Part A1a: Identify ESINQ Effects and Expected Impacts

The intent of this step of the IMDP is to build an understanding of the ESINQ effects the user is trying to implement in the model, as well as the expected impacts of these effects. The IMDP accomplishes this goal through a simplified process that walks the user through the initial intent of the overall study through the definition of the ESINQ effects of interest. This process can be seen in Table 13.

Table 13. IMDP: Part A1a

1	Develop the Operational Concept							
	-	What is the purpose of this study? What is it you are trying to get the model to do?						
2	Identify the ESINQ effects are you trying to represent in your model							
	-	List the ESINQ effects						
	-	Are these Internal, External, or both?						
3	Describe the impacts of these ESINQ effects							
4	Record findings in the EEMM							

As shown in Table 13, this step has just four sub-steps to facilitate an expanded understanding of the ESINQ factors of interest and begins with the user defining the purpose and intent of the study through the development of the OC. While the OC can have many forms, in terms of modern MDPs and this research, the OC should address the questions described in Table 14.

Table 14. Typical OC for M&S

1	What are you trying to investigate?
2	What type of study are you attempting? (Live/Virtual/Constructive)
3	What is the purpose of the study? (Descriptive/Prescriptive/Predictive)
4	What are the desired Factors, Responses, MOPs, MOEs?
5	What level of the model hierarchy do you want?
6	Deterministic vs. Stochastic?
7	What level of resolution is needed?
8	What are the requirements for VVA?
9	Time-Step vs. Discrete Event?
10	What are your analysis requirements? What results are you looking for?

While the OC is a foundational document, and thus fairly detailed, for the purposes of this demonstration a simplified OC will be more than adequate. To set the conditions for the execution of the IMDP, the following OC will be used to support the scenario described in part A.

1. The overall purpose of this investigation is to quantify the impacts from adversary space-based ISR degradation on the RCP of friendly forces. Thus, I want to quantify the impacts to combat effectiveness with and without degradation of space-based ISR within the context of a D3SOE.

2. Because of the significant number of simulation runs required to fully explore the tradespace, as well as the limited time and resources available, I will only be considering constructive simulations. While live and Virtual M&S tools have potential merits with respect to my work, they have resource requirements beyond my capacity as a student researcher.

3. This will be a mixed methods study in which I will be interested in both the descriptive nature of the model to highlight the potential impacts from a D3SOE, as well as the predictive nature of the model to allow comparison of potential alternatives to develop more robust solutions.

4. The primary evaluation metric for this study will be measures of combat effectiveness. Thus, I will need an M&S package capable of taking

combat related mission and noise input factors, and in return provide combat related responses from the perspective of ground forces, like P_v, casualties, length of battle, communications, and shooter-target info.

5. I am looking for a ground combat model that can accurately model BN and BDE level operations, to include reliance's on reach back support from space. Thus, a mission level model is most appropriate.

6. Because I am interested in combat, and that combat is by nature inherently chaotic, a stochastic model is preferred.

7. Because this is a proof of concept, and time and resources are limited, I will be looking for a relatively low resolution model. While not as accurate in its representation of the OE, it will meet the intent of this research and can be improved in the future with a higher fidelity model.

8. Because this is a proof of concept, where I am attempting to develop a methodology and tools for supporting operational and acquisitions decisions, a fully VV&A model is not necessary; face/peer model validation should more than meet my need.

9. Through the execution of the MSSSM, primarily for simplicity, ease of use, access, and support, a time-step model was selected for my work.

10. With regard to analysis, I am interested in the output of the simulation, specifically how a given set of input factors affect the output response of combat effectiveness. I will also be interested in the behaviors of the M&S as it progresses. So, I will need an package that produces outputs throughout execution, to include summary statistics at the conclusion.

Following my codification of the OC, where the context and boundaries of the study are established, ESINQ factors of interest can be identified. The initial identification of ESINQ effects should focus on capturing the essence of the effect, without any consideration for the feasibility of capturing or representing those effects. For this demonstration, the ESINQ effect of interest to me was the effect of ISR degradation on combat operations. Next, I describe in as much detail as possible the expected impacts of ISR degradation on combat operations, a summary of which can be seen in Table 15.

Table 15. ESINQ Expected Impacts

3	Describe the impacts of these ESINQ effects		
	-	Impacts to SA due to degradation of ISR collection capacity.	
		o	Reduced SA accuracy, less complete COP.
		o	Reduced availability and decreased timeliness of current intel.
		o	Slower fulfillment of ISR requests.
		o	Decreased speed of battle and responsiveness.
		o	Increased uncertainty regarding understanding of friendly and enemy activities.
		o	Decreased availability of ISR collection assets.
		o	Impacts increase at higher echelons and as the duration of degradation increases.
		o	Larger dependency on other, less capable means of ISR.
		o	Increased uncertainty of locational and targeting data, friendly and enemy.

The detail here is similar to brainstorming and should include any and all potential impacts, regardless of the appropriateness, based on the purpose of the study as outlined in the OC. The intent is to generate a large set of potential impacts to build a better understanding of the ESINQ effects prior to identification of tangible effects and the selection of the M&S package. Following the description and consolidation of the expected impacts, the EEMM is instantiated to translate ESINQ factors of interest into tangible and compatible factors within the selected model. Table 16 shows the instantiation of the EEMM for the scenario in this chapter.

Table 16. EEMM: Part A (Degraded ISR)

ESINQ Effect	Expected Impacts
Degraded ISR	Reduced sensing capabilities and periodic sensor blinding
	Reduced pace of battle, Decreased SA
	Reduced collection capacity / decrease in capabilities

As shown in Table 16, degraded ISR is the ESINQ factor of interest in this example, and I have instantiated the EEMM by listing a few expected impacts from degraded ISR on combat operations. While this example is simplified, and lacks what I would consider a sufficient amount of detail to fully describe the impacts of degraded ISR on actual combat operations, it is sufficient for the purposes of this demonstration.

With the ESINQ factor of interest identified, and the expected impacts codified, I can now link these expected impacts to tangible operational effects.

b. *Part A1b: Linking ESINQ and Tangible Effects*

The intent of this step of the IMDP is to refine the understanding of the ESINQ impacts gained during A1a by linking them to a set of tangible effects that can potentially be used to represent them within the model. The IMDP continues the process introduced in step A1a, leading the user to a better definition of the ESINQ effects of interest through a process of brainstorming and informed subjective assessment, which can be seen in Table 17.

Table 17. IMDP: Part A1b

1	Link ESINQ Expected Impacts to Tangible Effects.		
	-	For each ESINQ factor:	
		o	List all potential tangible effects that the expected impacts listed in part A1a would have on your model.
2	Record findings in the EEMM.		

As shown in Table 17, this step focuses on refining the understanding of the ESINQ effect by producing a more detailed list that links the potential effects from part A1a to tangible effects which can potentially be used to represent the ESINQ effects in the model. Table 18 provides a simplified list of tangible effects that could potentially be used to represent the impacts of degraded ISR within the model.

Table 18. ESINQ Tangible Effects

1	Impacts to SA due to degradation of ISR collection capacity		
	-	Reduced SA accuracy, less complete COP	
		o	Delays in operations, decreases in Ph, increased Frat, slower pace of battle
	-	Reduced availability and decreased timeliness of current intel	
		o	Reduced number of PIRs can be addressed, less intel generated, data is older, targetable intel is reduced
	-	Slower fulfillment of ISR requests	
		o	Less responsive execution of ISR requests, less ISR available, slows pace of battle, forces Cmdrs. to source ISR requirements to internal and less capable systems.
	-	Decreased speed of battle and responsiveness	
		o	Slower pace of operations, forces friendly forces to be more reactive than proactive.
	-	Increased uncertainty regarding understanding of friendly and enemy activities	
		o	Increased intel error of enemy locations, dispositions, strength, systems, ect, coupled with a slower and less complete understanding knowledge of friendly and enemy interactions
	-	Decreased availability of ISR collection assets	
		o	Less collection capacity, prioritization of ISR requests increases intel delays, lower echelon forces receive less actionable intel.
	-	Impacts increase at higher echelons and as the duration of degradation increases.	
		o	Strategic ISR requirements begin to take priority over tactical ISR requirements in order to meet national requirements, significantly reducing the ISR collection capabilities of the operational force, decreasing pace of operations, SA, and causing
	-	Larger dependency on other, less capable means of ISR	
		o	Lack of actionable intel and accurate SA forces CMDRs to source operational ISR requirements to local sources like UAVs, and ground recon teams, which are far less capable and take much longer to execute, thus drastically delaying the intel building associated with combat planning and execution.
	-	Increased uncertainty of locational and targeting data, friendly and enemy	
		o	Decreased speed of the targeting cycle as it becomes more difficult to obtain targetable intel, coupled with a decrease in Ph due to the combination of locational uncertainty and delay in intel gathering

By linking expected impacts to potential tangible effects, I am able to build a better understanding of the impacts of degraded ISR on the model, which is important because the understanding gained here will help screen and select an appropriate M&S package for use within the study. Following the identification and codification of these tangible effects, the EEMM is further expanded to demonstrate the linkages between expected impacts and tangible effects, which can be seen in Table 19.

Table 19. EEMM: Part B (ISR Degradation)

Expected Impacts	Linking	Tangible Effects
Reduced sensing capabilities and periodic sensor blinding	→	Slower speed, more recon, decreased SA, decreased Pd/Pc of Ext systems
Reduced pace of battle, Decreased SA	→	Slower speed, increased LOB, increased Advantage to Defender
Reduced collection capacity / decrease in capabilities	→	Decreased Ph of indirect fires, decreased Pd/Pc of Ext systems

As shown in Table 19, the IMDP supports the identification of a list of tangible effects that can potentially be used within a model to represent the impacts to operations from degraded ISR. My next step was to take this list of tangible effects, and use it to drive my search, assessment, and selection of an appropriate M&S package for my study.

c. Part A1c: M&S Suitability Assessment and Selection

The intent of this step is to investigate and assess potential models for suitability and then select one for my study. My intent here was to two fold. I was looking for an M&S package with enough resolution to represent as many of the tangible effects identified in A1b as possible, as well as one with enough flexibility to meet as many of the primary and secondary considerations identified in OC. For this assessment, I used the MSSSM provided by the IMDP, the basic steps of which can be seen in Table 20.

Table 20. IMDP: Part A1c (MSSSM)

Investigate Models and identify a Model with appropriate factors which can best model the tangible impacts from Step B, that can be used as surrogates for the intangible effects.	
A	Develop the M&S Operational Concept.
B	M&S Review and Screening.
C	Initial Screening.
D	Secondary Screening.
E	Model Exploration (for each remaining M&S package).
F	M&S Comparison and Evaluation.
G	Conclusion and recommendation.
H	Application (EEMM).

The MSSSM provided me with a formalized methodology for assessing my needs of an M&S package, and then guiding me through the review, screening, exploration, assessment, and finally, the selection of an appropriate package. Because of the complexity of MSSSM, it is not described in detail here, but all 60+ pages can be found

in Appendix A. Following the completion of the MSSSM, I constructed a weighted decision matrix to compare the top three M&S packages as seen in Table 21.

Table 21. M&S Weighted Selection Matrix

Weight	Factors	MANA	JDAFS	SEAS
6	Ability to Simulate a D3SOE	3	2	5
5	Support Availability	5	4	2
5	Cluster Access	5	4	2
5	Ease of Use	5	2	3
4	Rapid Development	4	2	2
4	Existing Models	5	2	2
4	Ease of Analysis	4	3	3
4	Output Data Density	4	3	4
3	Learning Curve	4	2	4
3	Behavior Monitoring	4	2	3
3	DOE Tools Available	5	3	2
2	Ease of DOE Execution	5	2	2
	Total Value	210	127	140

As shown in Table 21, my execution of the MSSSM for my dissertation research identified three potential M&S packages. The first was MANA, a time-step and agent based ground combat model. The second was JDAFS, a discrete-event modeling framework. The third was SEAS, an air and space time-step modeling framework. Based on the weights and factors that I established through the execution of the MSSSM, which included considerations for my needs and resources, MANA achieved the highest value score. Thus, MANA was used throughout my research as well as this demonstration. Following the selection of MANA as my M&S package, I identified the MANA surrogate factors that could best represent the tangible effects described in A1b and then expanded the EEMM, which can be seen in Table 22.

Table 22. EEMM: Part C (ISR Degradation)

		Factor	Maps
Tangible Effects	Mapping	ANA Potential Surrogate Facto	
Slower speed, more recon, decreased SA, decreased Pd/Pc of Ext systems		Agent Speed	2
Slower speed, increased LOB, increased Advantage to Defender		Ph / Discharge	1
Decreased Ph of indirect fires, decreased Pd/Pc of Ext systems		Ave Time/Det	3
		Pc	2
		Rate of Fire	1

The expanded EEMM shows the mapping of tangible effects to a set of surrogate factors that can be used to represent the impacts from degraded ISR that I identified within MANA during the execution of the MSSSM. This mapping serves two primary purposes. First, it identifies the surrogate factors that can represent the most tangible effects, which can support weighting of factors for inclusion in the model. Second, the mapping ensures traceability from surrogate factors, through tangible effects and expected impacts, back to the original ESINQ factors of interest. The intent of the last three steps was to manipulate the effect of degraded ISR into a form which could be understood and implemented by the model.

d. Part A2a: Selection of a Reference Tool

The intent of this step of the IMDP is to select an appropriate reference tool for use during the calibration of the model. While the IMDP does not provide a formalized process here, it did provide me a framework to navigate numerous key considerations prior to selecting the reference tool. This directed exploration of potential tools is much more likely to produce an appropriate tool than would have been achieved otherwise. The general process of this step can be seen in Table 23.

Table 23. IMDP: Part A2a

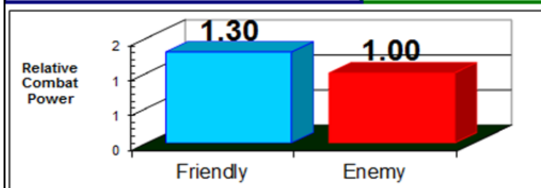
1	Select an appropriate reference tool		
	-	The reference tool will support the calibration of the operational model, as well as a validation method for linking the expected outcomes of the tool and the model.	
	-	It is important to consider the intent of the study and the desired outcome before choosing an appropriate reference tool.	
	-	The following considerations should be made with regard to the reference tool. These serve as a framework to guide the user through a set of key considerations that should be addressed prior to the selection of a reference tool:	
		o	Consider the OC of the selected model, the tool should be similar nature.
		o	The tool can be anything from a data spread sheet, a user tool, or another model.
		o	If the intent is for the model to inform another tool, then consider that tool.
		o	The reference tool should include an accessible set of source data.
		o	The tool should be comparable in size, scope, and resolution to the model.
		o	The tool should facilitate validation of the model.
		o	The tool should have a set of outputs that are in common with the model.
		o	The tool should be expandable once informed by the model.
		o	The tool should provide utility to the user outside of its linkages to the model.

This framework supported my selection of an appropriate reference tool by leading me through a set of questions that forced me to scope and screen potential tools based on intended need. For this dissertation, as well as for this demonstration, the IMDP led me to the selection of the Army's FRC. This tool, originally designed in 1999 by Major J. Craig during his CGSC course work, is currently the most commonly used operational planning tool for accessing the combat power of opposing forces. After considering its purpose, its commonalities with combat models, as well as my interest in expanding it to account for the impacts from ESINQ factors, the FRC is more than appropriate for use as my reference tool. The FRC, instantiated for a scenario similar to what was introduced in part A, can be seen in Figure 55.

Force Ratios

Friendly Forces					Enemy Forces				
Number	*Strength*	*Type*	*F.E.*	*Total*	*Number*	*Strength*	*Type*	*F.E.*	*Total*
1	100%	Armor Bn (44 x M1A2)	1.30	1.30	1	100%	Tank Bn (MIB 40xT80)	1.00	1.00
Friendly Force Equivalent				**1.30**	Enemy Force Equivalent				**1.00**

Ratio of Friendly to Enemy 1.30:1		Ratio of Enemy to Friendly 0.77:1
Hasty Attack 15%	<- Mission -> <- Est. Losses ->	Hasty Defense 15%



Instructions:
1. Select type of unit from drop down list.
2. Input number and type. If less than a whole unit use fractions (e.g. 1 Btry = .33 Bns).
3. Use comparison of force ratios (graph) and historical planning ratios.
4. To calculate damage to each unit, select the friendly and enemy mission from the list.

Remember: Relative force ratios do NOT necessarily indicate the chance for success for either force!

Historical minimum planning ratios.		
Friendly mission	*Friendly : Enemy*	*Position*
Delay	1 : 6	
Defend	1 : 3	Prepared or fortified
Defend	1 : 2.5	Hasty
Attack	3 : 1	Prepared or fortified
Attack	2.5 : 1	Hasty
Counterattack	1 : 1	Flank

Figure 55. FRC (Tank versus Tank)

The FRC was instantiated to compare the RCP of two opposing tank battalions, which is the focus of the example we are using in this demonstration. What one should notice immediately is that the tool does not address the impacts from ESINQ effects in any meaningful way. This is ok, because while it cannot account for the impacts from degraded ISR, it does have many similarities with combat models like MANA, which can be linked and calibrated to our selected model through metrics of combat effectiveness. Additionally, the source data that drives the FRC is based on the Army’s COFM and FA-SWN spread sheets. These documents are detailed enough to support the identification and segregation of internal and external sources of combat power, and thus, the FRC is an excellent reference tool, and its source data will be used for my normalization efforts.

e. Part A2b: Normalization of the Reference Tool

The intent of this step is to establish an accurate baseline for the calibration and development of the model by removing any potential ESINQ-enabled bias from the reference tool. With regard to the FRC, this bias was identified after inspection of the source data; where I discovered that the FA-SWN did not delineate between internal and external sources of combat power derived from C4I, one of the five primary contributors to a system's overall combat power. Likewise, the FA-SWN was inconsistent in how it assessed a system's C4I contributions to combat power, to the extent that some systems accounted for it and others did not. Thus, any exploration of the potential impacts of ESINQ factors on C4I could lead to inaccuracies in the expected outcomes of the model due to its inability to distinguish between sources of C4I derived combat power. The framework in Table 24 provided an efficient means for removing the bias identified in the FA-SWN by separating internal and external sources of C4I derived combat power, assessing and tracking the individual contributions of C4I based on system tier.

Table 24. IMDP: Part A2b

1	Start with a clean version of the Force Analysis Systems Weights Spreadsheets.							
2	Delete any C4I contributions to relative combat power.							
3	Calculate the new FE, include C4I contributions, of all system based on the system Tier level by multiplying the base FE by the C4I dependency factor you choose below.							
	-	Tier I	1.60					
	-	Tier II	1.40			F.E.	New F.E.	
	-	Tier III	1.25		MIA2	8.35	13.36	
	-	Tier IV	1.10					
4	Calculate the C4I contribution of each system by subtracting the base FE from the new FE. Below is an example for the M1A2							
						F.E.	New F.E.	C4I
					MIA2	8.35	13.36	5.01
5	Separate the Internal and External C4I contributions based on the Tier of the system based on the values you select below. For example, 50% of C4I capabilities of a Tier I system are derived external of the system.							
	-	Tier I	50%	** Internal C4I factors will stay in the combat model as "sensor and SA attributes".				
	-	Tier II	30%					
	-	Tier III	20%	** External C4I factors will be accounted for separately on the IRCPAT.				
	-	Tier IV	10%					
						C4I	Internal	External
					M1A2	5.010	2.505	2.505
6	Update the Force Analysis Systems Weights Spreadsheets with the new FE (including internal C4I contributions)and separately, the External C4I contributions.							
						F.E.	External	
					M1A2	10.855	2.505	
7	Copy these two values for each system into the data tab of the IRCPAT.							

The M1A2 used in my example was normalized following seven general steps. First, the C4I contribution was removed, which removed the observed inconsistency of C4I contributions from system to system. Second, a new Force Equivalent (FE) was calculated based on its tier level. The total C4I contribution was then calculated from the difference and the contributions from both internal and external C4I was calculated based on the system's tier level. Finally, the internal element of the C4I was added back into the system's total FE, and the remaining external C4I contribution was tracked separately, which served to effectively strip out the observed bias due to external dependencies. With the bias removed, or more appropriately, reallocated and accounted for separately, the updated FE for the M1A2 could now be used to modify the FA-SWN, a portion of which can be seen in Table 25.

Table 25. Improved FA-SWN FRC (Tank versus Tank).
Adapted from (U.S. Army 2004).

Vehicle	Combat Potential	System Tier Level(s)	Tier C4I Modifier	New Combat power	Contribution of C4I	External C4I Modifier	External C4I FE	Internal C4I FE	Internal System Combat Power (to include Internal C4I)
Main Battle Tanks									
US MBT M1A2	8.35	1	1.60	13.36	5.01	0.50	2.505	2.50	10.855
Rus MBT T-80U	7.19	2	1.40	10.07	2.88	0.30	0.863	2.01	9.204
							Captured in Improved Relative combat power Assessment	This needs to be imparted into the model sensors	Captured in Improved Relative combat power

The FA-SWN was updated for the two types of tanks used in this demonstration to remove any bias due to the dependencies of C4I on external contributors of combat power. For my work, this update decreased the internal combat power of the U.S. tanks by shifting some combat power to external contributors and increased the overall combat power of adversary tanks by giving them credit for external elements of combat power that were previously ignored. Once updated, the FA-SWN provides the user with a more accurate assessment of the combat power of opposing forces, which clearly delineates between internal and external sources of combat power. For example, after taking these normalized tank values and inserting them back in to the reference tool, the FRC yielded a RCP estimate of 1.18:1, a decrease from the 1.30:1 seen in Figure 58 prior to the normalization. This difference is expected when considering the bias that was included in the original FA-SWN and highlights how normalization can help better articulate it.

f. Part A3a: Baseline Calibration

The purpose of baseline calibration is to establish a foundation for the incremental calibration of mission, agent, external dependencies, and ESINQ factors. The general process for baseline calibration can be seen in Table 26.

Table 26. IMDP: Part A3a

1	Instantiate the reference tool.	
	-	Rank order the contributors of combat power from highest to lowest.
	-	Instantiate the reference tool for the most significant of the agents above, as Blue and Red, with a Force ratio 1:1, 100% strength, and 0% External C4I or ESINQ factors.
2	Build a simplified model using the agent type noted above.	
	-	Use a neutral battlefield where no advantages are gained.
	-	Opposing agents should have identical system attributes based on the a system of interest.
	-	Perform incremental development of the model to ensure a 50% victory rate (+/- 2%).
3	Force Ratio Attributes: Determine the range of the Force Ratios based on the mission set.	

The first step, instantiated of the reference tool, focuses on modifying the IRCPAT to establish a baseline for calibration, which provides a starting point for linking the model to the reference tool. To do this, I instantiated the IRCPAT as closely as possible to the operational scenario based on the OC. Once complete, I rank ordered the contributors of combat power from highest to lowest, and identify the top 2–3 agents that contribute the majority of combat power. Of these, I selected the agent type with the fewest number of agents. The reason I want to use the most significant of the agents is because the calibration steps that follow will produce more accurate outcomes. For this demonstration, I only have two agent types, and thus the M1A2, which is more capable than the T-80U, will be used. Next, a new IRCPAT is instantiated using just the M1A2, while reducing the complexity by removing all variables that can differentiate a system advantage, which included FR, mission, agent, external dependencies, and ESINQ variables. The updated IRCPAT can be seen in Figure 56.

Improved Relative Combat Power Assessment Tool (IRCPAT)

Ratio of Friendly to Enemy							Enemy Forces						
Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total	Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total
20	100%	Armor (M1A2)	10.85	217.00	2.50	50.00	20	100%	Armor (M1A2)	10.85	217.00	2.50	50.00

Friendly			Enemy		
System Force Equivalent		217.00	System Force Equivalent		217.00
External Force Equivalent		50.00	External Force Equivalent		50.00
Status of External C4I	0%	0.00	Status of External C4I	0%	
ESINQ Effects			ESINQ Effects		
Status of ISR Degradation	0%	0.00			

External Systems			External Systems		
Number	Strength	Type	Number	Strength	Type
0	100%	SmallSat (ISR)			

Friendly	Enemy
Friendly Force Equivalent 217.00	Enemy Force Equivalent 217.00
Ratio of Friendly to Enemy 1.000:1	Ratio of Enemy to Friendly 1.000:1

Friendly			Enemy	
Hasty Attack		<- Mission ->	Hasty Attack	
4.0	20.2%	<- Estimated Losses ->	20.1%	4.0
0.492		<- Estimated % Victory (Curve 1) ->	0.508	
0.498		<- Estimated % Victory (Curve 2) ->	0.502	
0.508		<- Estimated % Victory (Curve 3) ->	0.492	
0.504		<- Estimated % Victory (Curve 4) ->	0.496	

Figure 56. IRCPAT (Baseline)

As shown in Figure 56, the IRCPAT was instantiated using the MIA2 for both forces, without any advantage to either side due to force size, type, strength, mission set, C4I, ESINQ effects, or external dependencies. As expected with two identical forces, the IRCPAT assessed a RCP of 1:1, with an expected Blue P_v of roughly 50%. While the IRCPAT gives four potential victory curves for the user to choose from, Victory Curve 4 will be the only one used in this dissertation. Following instantiation of the IRCPAT, I can now develop the simplified model.

The intent of model development during this step is to build a small controlled experimental environment that will support the analysis of the impacts from factors of interest on equivalent forces during calibration. For model development, the IMDP is similar to traditional MDPs, with the only significant difference being the ability of the IMDP to account for the expansion of the model to account for Mission, Agent, ExtDep, and ESINQ factors. Using MANA, I constructed a simplified model where two sets of

identical forces were pitted against each other, and like the instantiated IRCPAT, would ignore all advantages of either side due to force size, type, strength, mission set, C4I, ESINQ effects, or dependencies. Despite the lack of detail regarding model development, this step was very time consuming, and required me to perform a significant amount of T&E to verify that the model was implemented correctly. Figure 57 is a screen shot of my MANA model.

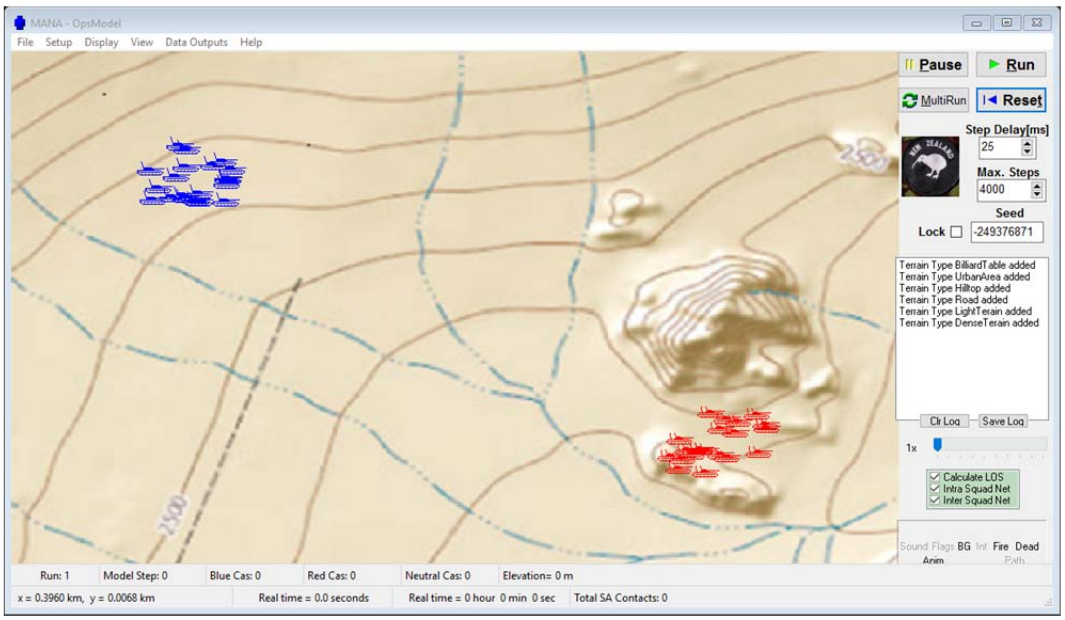


Figure 57. Simplified MANA Model (Degraded ISR)

As shown in Figure 57, the model consists of 20 Blue tanks (M1A2) facing 20 Red tanks (M1A2). All aspects of the expected OE as outlined in the OC are implemented within the model, other than the ESINQ effects of interest and any other ESINQ effect. The tanks of both sides have identical factor settings, personalities, and goals and thus, the execution of the model should produce a near draw between the forces. To verify, I executed a 1000 replication verification run of the model and the summary statistics can be seen in Figure 58.

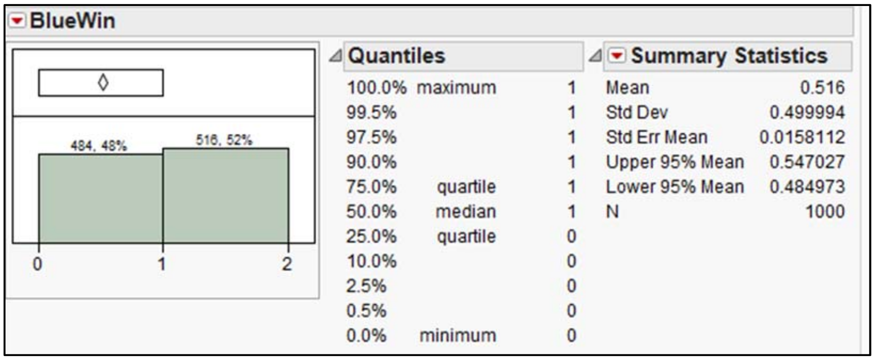


Figure 58. Summary Statistics (1000 Replications of Simplified Model)

The verification run of my model resulted in the Blue force achieving a P_v of 51.6%. The variation from the true mean of 50% is well within +/- 2% as suggested by the IMDP, and is easily accounted for by the stochastic variation of the MANA model due to the number of forces. Additionally, the 95% Confidence Interval (CI) shows a CI of 0.485 to 0.547, which captures the true mean of 50%. Thus, the verification run confirms that the model was implemented correctly and behaving as expected, and thus, I was able to move on to establishing the FR attributes.

The last step before calibration was to determine the FR attributes needed for my study. To do this, I used the tool provided by the IMDP to estimate the number of Blue forces needed, which can be seen in Table 27.

Table 27. IMDP: Part A3a-3

3 Force Ratio Attributes: These are required to support the functionality of the reference tool. Determine the range of the agent Force Ratios based on the specified mission set by fixing the size of the red force in the following table.

- For this example, a HA-HD, doctrine states that a FR of 2.5 to 1 will result in approximately a 50% chance of victory, thus:
  - For a HA-HD scenario with red fixed at 20, and Victory Range of 40% to 95%, we vary blue forces from 46 to 83.

Red Forces are fixed at: 20

		Victory Curve #3 (IRCPAT)		
		40%	50%	95%
B vs. R	Modifier	0.92		1.65
DD-HA	0.29	5	6	10
DD-DA	0.33	6	7	12
HD-HA	0.4	7	8	14
HD-DA	0.5	9	10	17
HA-HA	1	18	20	33
DA-HD	2	36	40	66
HA-HD	2.5	46	50	83
DA-DD	3	55	60	99
HA-DD	3.5	64	70	116

	Low	High
AvsD	36	116
DvsA	5	17
AvsA	18	33

The purpose here is to establish the range of Blue agents that will be needed to capture the full range of expected victories, which in this demonstration runs from 40% to 95%. To use the tool, I started my inputting the starting Red strength (20), as well as the victory range of interest for my study, which for me was a Blue P_v of 40–95%. Based on these values as well as the mission set of interest to me (HA-HD), the tool shows that the DOE will need to vary the number of Blue tanks from 46 to 83 to explore the full range of potential victory cases, with 50 Tanks giving the Blue force a P_v of 50%. With baselining activities complete, I can now begin calibration.

g. Part A3b: Mission Calibration

The intent of this step is to link the model to the IRCPAT through the establishment of mission specific attributes that can capture the advantage that the Red force has in defense while maintaining the synchronization of the expected victory between the tool and the model. Table 28 outlines the steps of mission calibration.

Table 28. IMDP: Part A3b

1	Update the reference tool by modifying it for the selected mission set and Force Ratio while maintaining a 50% expected victory.
2	Mission Calibration: Determine the range of the Mission Attributes based on the specified mission set of each force to define the "advantage" of the defending force.
3	DOE: Execute a multi-factor DOE of the calibration model by modifiying Force Ratio (#BlueTanks) and verify that the updated model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios.
4	Analysis: Conduct analysis to establish the baseline mission factor settings. - Trade-space exploration to minimizing variation form expected outcomes. - Record the Calibrated Mission Attributes as factor settings for use in the operational model.

I began mission calibration by expanding the IRCPAT to account for the specific mission of each force, which for this demonstration, was the Blue force executing a hasty attack and the Red force conducting a hasty defense. Following this modification, the number for Blue tanks was modified to maintain the expected Blue P_v at 50%. The expanded IRCPAT can be seen in Figure 59.

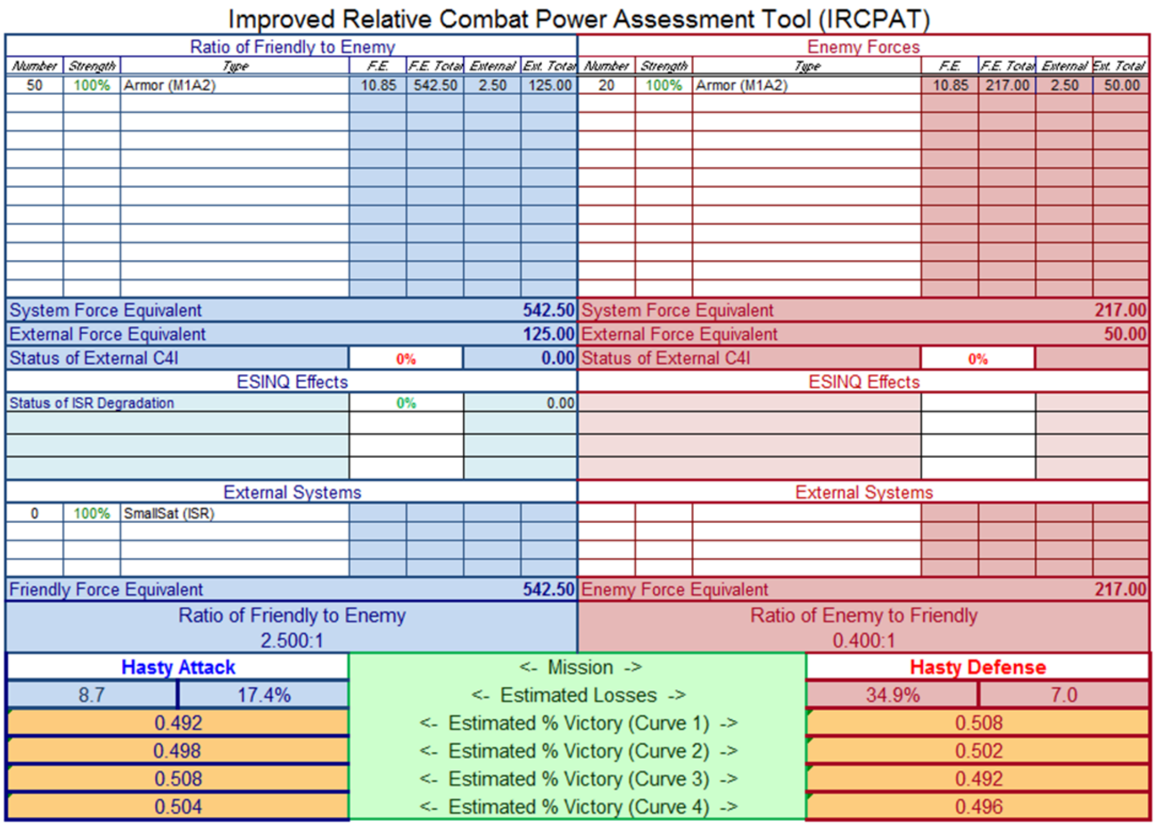


Figure 59. IRCPAT (Mission Calibration)

The IRCPAT has been updated to account for the mission set of the opposing forces. Thus, a significant shift in the RCP was seen, reducing the expected Blue P_v from 50%, to less than 5%, which was expected when considering the significant advantage of the defense. To overcome this advantage, I was forced to increase the FR of the Blue force to 2.5:1 (or 50 tanks) to maintain a Blue P_v of 50%. Following the expansion of the IRCPAT, my next objective was to attempt to represent this same advantage in the model through mission attribute calibration; the steps of which can be seen in Table 29.

Table 29. IMDP: Part A3b-2

2 Mission Calibration: These are attributes of each agent that are tied to the mission set, these help define "advantage" of defending forces. Determine the range of the Mission Attributes based on the specified mission set of each force by selecting the appropriate input values (Yellow cells) in the following table. If you do not wish to use this DOE calculator and already have an understanding of the required factor ranges, input them directly into the next table.

- Accounting for Misson Set Advantage: Because the baseline model gives no advantage for the deffense, some considerations need to be addressed to give the defending force an advantage over the attacking force. This is meant to capture the majority of the advantage, and is a brute force manipulation of potnetial outcomes. The misison calibration steps that follow will serve to "fine tune" this manipulation in order to achieve a stable outcome across all possible force ratios.
  - o Set cover for the defending force as follows:

Hasty Defense:	60%		Deliberate Defense:	75%

- For MANA this requires the addition of a terrain feature to denote cover.
- If this is not enough, another option is to reduce the 0m (Max) Ph of the attacker

Attacker:	0.75	Defender:	0.95

- For this example, the following multiplication factors were used.

Modifiers	HA	DA	HD	DD	Ph Combo Mod		
Pers Conc	0.30	0.40	0.60	0.80	DD-HA	1.00	0.12
Ph Against	1.00	0.90	0.60	0.30	DD-DA	0.90	0.18
Ph From	0.40	0.60	0.90	1.00	HD-HA	0.90	0.24
RateOfFire	0.40	0.60	0.80	1.00	HD-DA	0.81	0.36
Speed	0.60	0.80	0.00	0.00	HA-HA	0.40	0.40

- Transfer these values to the "Mod" columns in the DOE Factor Setting Tool Below.
- Insert your "Maximum" values (in the format accepted by the model for that factor) into the DOE Tools based on knowledge and expected performance of the systems being modeled.
  - o Blue Hasty Attack vs. Red Hasty Defense

	Mod	Max	DOE Low	Model	DOE High
Blue Concealment	0.30	90	10	27	57
Red Concealment	0.60	90	24	54	84
Blue Ph (at 3500m)	0.24	0.40	0.05	0.10	0.30
Red Ph (at 3500m)	0.90	0.40	0.16	0.36	0.40
Blue RoF (#/100)	0.40	30	5	12	27
Red RoF (#/100)	0.80	30	9	24	30
Blue Speed	0.60	48	10	29	48
Red Speed	0	0	0	0	0

The IMDP provides a framework and tools for addressing the selection of potential mission attributes in two distinct ways. First, it established a few broad mission attributes that can best represent the advantage of the defending force seen in the IRCPAT. For this demonstration, I gave the Red force 60% cover and reduced the 0m P_h of the Blue force to 0.75. This adjustment effectively gave the Red force a significant advantage over the Blue force that can be attributed to the advantage of the defense. Next, to give me the ability to fine tune the response (P_v) of the model during the DOE, I used the five factors recommended by the IMDP and inputted my expected multiplication factors for each of the five factors for each of the four general mission areas. For example, I assigned a force conducting a hasty attack a concealment value of 0.30, while giving the defending force (hasty) a concealment value of 0.60. I did this for all combinations, resulting in a logical relative hierarchy that characterized the advantages of one mission set over another. Following my assessment, I transferred the specific mission values and the P_h Combo Mod (HA-HD) into the DOE range tool, and after inputting the maximum value for each of the attributes, the DOE min and max values for each of the four factors (Red and Blue) were calculated. Following the establishment of the DOE factors and ranges, the design was constructed as described in Table 30.

Table 30. IMDP: Part A3b-3

3	DOE: Execute a multi-factor DOE of the updated model by varying Force Ratio and any Agent attribute identified above in order to verify that the updated model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios after agent calibration.				
	- Set your Design Points based on the work from above, modifying just the Mission attributes noted above. Ensure you provide adequate trade space to explore each factor setting.				
	o Stack 1 (Attack vs. Defense).				
		DPs	Factors	Low	High
	FR Attributes	1	# Blue Tanks	46	83
	Mission Attributes	2	Blue Concealment	5	50
		3	Red Concealment	30	90
		4	Blue Ph (at 3500m)	0.05	0.25
		5	Red Ph (at 3500m)	0.20	0.60
		6	Blue RoF (#/100)	5	20
		7	Red RoF (#/100)	15	40
		8	Blue Speed	10	48
		9	Red Speed	0	0
	- Select and Build your Design.				
	o Determine the number of Factors (8 in this example).				
	o If the number of factors is 13 or less, use a 2nd Order NOLH design. If it is greater than 13 up to 29, use a NOLH design. Both the NOLHdesigns.xlsx and the MacCalman-2ndOrderNOLH design tools can be found at https: //harvest.nps.edu/ .				
	o Download the DOE tool and input the values from the previous step.				
	o Consider conducting a screening design to determine significance, this may allow you to reduce the number of factors, and thus, use a more detailed 2nd order design in subsequent analysis.				
	- Stack the design.				
	o Stack the design to achieve better resolution within the design space as well as the solution space, which will provide better fitting models. Remember to vary the columns when stacking.				
	- Execute the DOE.				
	o For my work I provided the following files to the NPS SEED Center in order to run my model on the advanced computing cluster.				
	1	MANA Model .xml			
	2	The Design developed using the DOE above (translation to the .csv is needed)			
	3	The Study .xml script (this executes the model and design on the cluster)			
	- The SEED center can assist in preparing these documents for execution if needed.				

The purpose of this step is to select and build an appropriate DOE to support the identification of steady state values for the factors that will represent the impact of the mission set on P_v. For this demonstration, rather than selecting a nine-factor 2nd order NOLH design as the IMDP suggests, I chose to use a much simpler NOLH design to save resources. The simpler design resulted in a much smaller design, just 33 DPs opposed to the 265 DPs required by a 2nd order NOLH design, and once stacked nine times and replicated 100 times, resulted in a 29,700 DP simulation run. This design, the model, and

study execution file were then uploaded to the NPS advanced computing cluster, and the output data was returned for analysis; the steps of which are explained in Table 31.

Table 31. IMDP: Part A3b-4

4	Conduct analysis of the DOE output in order to establish the Mission Attributes for the HA-HD mission which results in the least variation between the model and the IRCPAT expected Blue Victory % across the full range of potential force ratios.
-	For this work, I used JMP to conduct regression analysis, and then used the contour profilers to identify Mission settings for each mission set that kept variation of the mean less than +/-5% from the expected victory based on victory curve #4.
-	Ranges for analysis should be based on the mission set. Below is the suggested Force Ratio Ranges for each mission set, both bounding and calibration, based on victory curve #4 of the IRCPAT.

		Force Ratios for % Victory				
	Mission Set	Bound Low (40%)	Calibrate Low (50%)	Calibrate High (90%)	Bound High (95%)	Force with Speed = 0
Defense vs. Attack	DD-HA					Blue
	DD-DA					Blue
	HD-HA					Blue
	HD-DA					Blue
	HA-HA					Neither
Attack vs. Defense	DA-HD					Red
	HA-HD	2.37	2.50	3.22	3.48	Red
	DA-DD					Red
	HA-DD					Red

-	Ensure that the solution space is saturated. If the output data produced outcomes that heavily favors victory of one side over the other, then the meta-models generated from that analysis will be skewed in that direction. To ensure that this bias is removed, you must ensure the solution space has a nearly equally distribution of outcomes above and below the expected victory curve. A 10% variation (40/60% split) is acceptable, any more and the DOE ranges above will need to be extended in the direction that favors the looser.
-	Each set of Mission attributes should result in a mean Pv of blue forces being within +/- 5% of the expected victory curves as described in the IRCPAT across the full range of force ratios ranges (Calibration low to Calibration high) as seen above, while attempting to maintain the relative hierarchy and order of each factor in relation to itself in other mission sets as seen in the table below.
-	Following the analysis and contour profiling exploration, record the Baselined Mission Attributes that minimize the variation between the Pv of the model and the reference tool across the calibration range of force ratios noted above. These will be used as the baseline factor settings in the model.
-	Execute a 1 x factor DOE of the updated model by varying only Force Ratio (#BlueTanks), and verify that the updated model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios.
-	For more accurate "Mission Attributes" calibration, repeat these steps for other mission sets. While this is may not be necessary, if the time is available, it is advised.

The primary purpose of this analysis is to estimate a set of factor settings that will capture the impacts of the HA-HD mission set on the P_v, while maintaining the models calibration to the reference tool (+/- 5%) across all possible FRs. To do this, I started by

ensuring that the solution space was saturated by plotting the responses (P_v) for each DP across the range of potential FRs and comparing the results to the expected victory curve. Figure 60 shows the solution space plot for mission calibration.

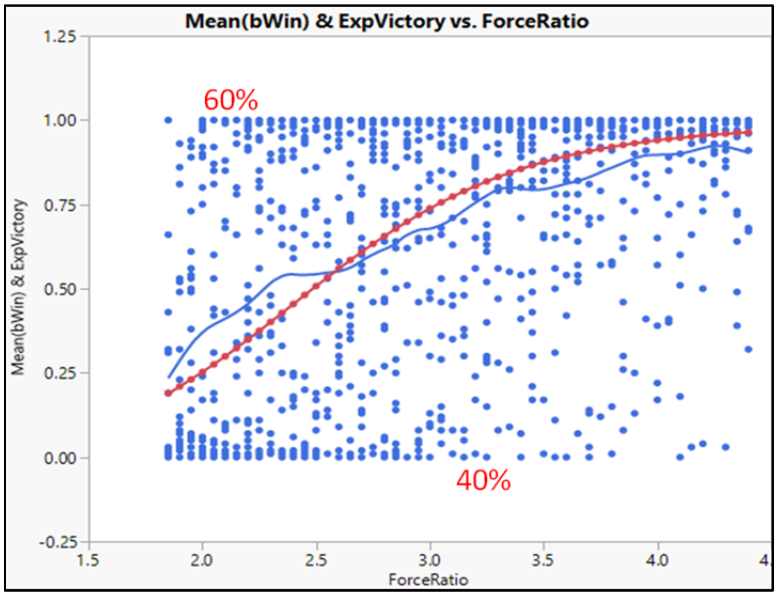


Figure 60. Mission Calibration DOE Solution Space Saturation

As shown in Figure 60, the distribution of the DPs meets the IMDP criteria for being considered saturated, in that the total deviation between the upper and lower distributions is 10%. With saturation of the solution space validated, I could then use JMP to conduct the statistical analysis, regression, and contour profiling needed to determine the settings of the mission factors settings. The JMP contour profiler can be seen in Figure 61.

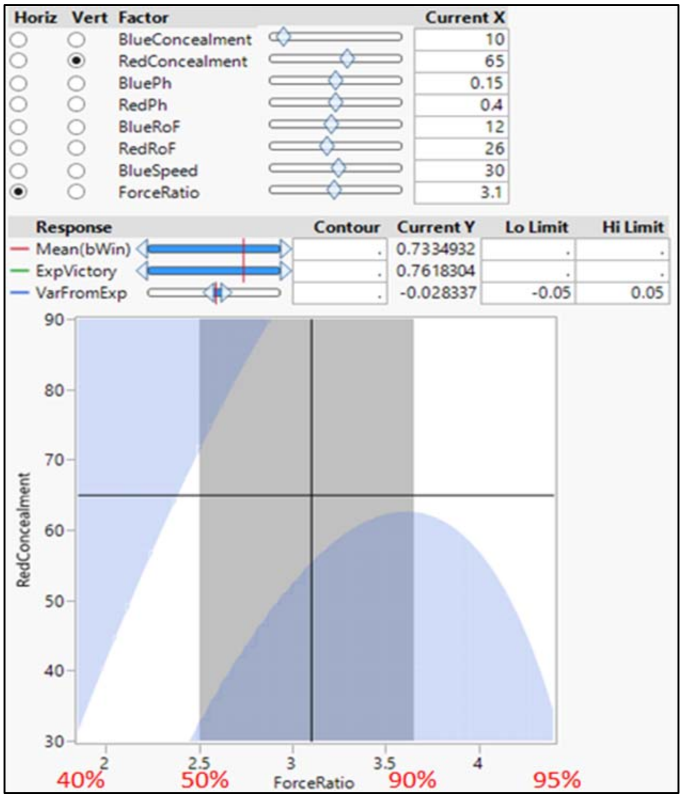


Figure 61. Contour Profiler of Mission Attributes

By setting the maximum variance between mean P_v and the expected P_v from the IRCPAT to +/-5%, and then conducting TSE, I was able to identify specific factor settings for each of the eight mission factor settings that ensured consistent results across the FRs of 2.50 to 3.66. Thus, using these factor settings, the model was now calibrated to the reference tool, and should produce results that will fall within +/-5% of the results of the IRCPAT across all FRs of interest (2.50 to 3.66 in this example). These settings were then recorded for future inclusion in the model and can be seen in Table 32.

Table 32. IMDP: A3b-4 (Results)

	HA	HD
Conc	10	65
Ph	0.15	0.4
RoF	12	26
Speed	30	0

These factor settings capture the mission dependent advantages of the defending force, and were used in the development of the model. With the mission factor settings recorded, the next step was to execute a one factor DOE, where I varied the FR to verify that the output of the model mirrors the expected results of the IRCPAT across the full range of potential FRs. The results of this analysis can be seen in Figure 62.

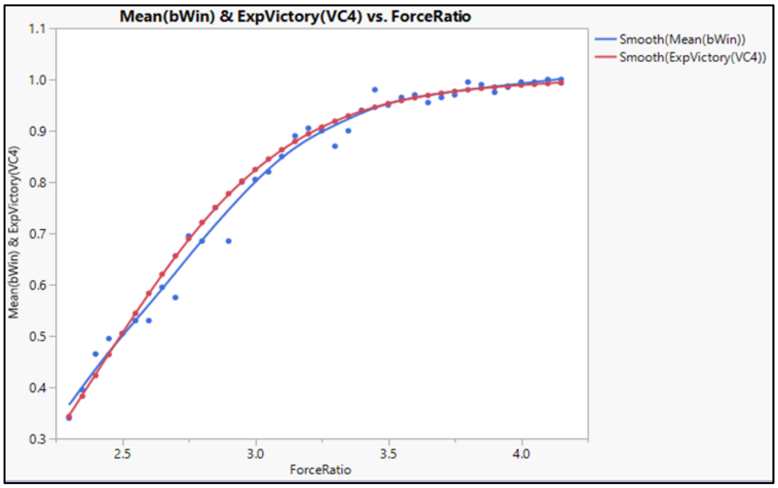


Figure 62. Mission Calibration Verification

As shown in Figure 62, the verification DOE confirmed that the Mission factor settings identified previously produced nearly identical results between both the model and the IRCPAT when implemented. Thus, the model was calibrated with the reference tool and capable of producing results that fall within +/- 5% of the IRCPAT across all FRs. With mission calibration complete, I moved on to building more functionality into the model by accounting for system specific attributes and capabilities that were ignored in mission calibration.

h. Part A3c: Agent Calibration

The intent of this step is to link the model to the IRCPAT through the establishment of agent specific attributes that can delineate between the differences of the opposing tanks, capturing the advantage that the M1A2 will have over the T-80U while

maintaining the synchronization of the expected victory between the tool and the model. Table 33 outlines the steps of agent calibration.

Table 33. IMDP: Part A3c

1	Update the reference tool by modifying it for the systems of interest, which will now differentiate between opposing forces.	
2	Agent Calibration: Calibrate the Agent Attributes for each agent to account for variations in capabilities based on the Improved Force Analysis System Weights Spread sheets to create the final "Agent Attributes" to be used in the Model.	
3	DOE: Execute a multi-factor DOE of the updated model by varying Force Ratio and any Agent attribute identified above in order to verify that the model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios after agent calibration.	
4	Analysis: Conduct analysis to establish the baseline agent factor settings.	
	-	Trade-space exploration to minimizing variation form expected outcomes.
	-	Record the Calibrated Agent Attributes as factor settings for use in the model.

I began agent calibration as before, by expanding the IRCPAT to account for the specific agents used for this demonstration, which included M1A2s for the Blue force and T-80Us for the Red force. Following the expansion, I modified the number for Blue tanks to maintain the expected P_v of the Blue force at 50%, which can be seen in Figure 63.

Improved Relative Combat Power Assessment Tool (IRCPAT)

Ratio of Friendly to Enemy							Enemy Forces						
Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total	Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total
43	100%	Armor (M1A2)	10.85	466.55	2.50	107.50	20	100%	Tank (T-80U)	9.20	184.00	0.86	17.20
System Force Equivalent						466.55	System Force Equivalent						184.00
External Force Equivalent						107.50	External Force Equivalent						17.20
Status of External C4I			0%		0.00		Status of External C4I			0%			
ESINQ Effects							ESINQ Effects						
Status of ISR Degradation			0%		0.00								
External Systems							External Systems						
0	100%	SmallSat (ISR)											
Friendly Force Equivalent						466.55	Enemy Force Equivalent						184.00
Ratio of Friendly to Enemy 2.536:1							Ratio of Enemy to Friendly 0.394:1						

Hasty Attack		<- Mission ->	Hasty Defense	
7.4	17.2%	<- Estimated Losses ->	35.3%	7.1
0.497		<- Estimated % Victory (Curve 1) ->	0.503	
0.510		<- Estimated % Victory (Curve 2) ->	0.490	
0.526		<- Estimated % Victory (Curve 3) ->	0.474	
0.533		<- Estimated % Victory (Curve 4) ->	0.467	

Figure 63. IRCPAT (Agent Calibration)

As shown in Figure 63, the IRCPAT was updated to account for the system level differences between the tanks of the opposing forces. Thus, a significant shift in the RCP was seen, which increased the expected Blue P_v from 50% to roughly 80%, which was expected when considering the superiority of the M1A2 over the T-80U. To take advantage of this increase in RCP, I decreased the number of Blue tanks needed to maintain a Blue P_v of 50% from 50 to just 43. Following the expansion of the IRCPAT, the IMDP directed me to execute agent attribute calibration, starting with system comparison of the opposing tanks; the steps of which can be seen in Table 34.

Table 34. IMDP: A3c-2 (System Comparison)

2 Agent Calibration: Calibrate the Agent Attributes for each agent to account for variations in capabilities based on the Improved Force Analysis System Weights Spread sheets to create the final "Agent Attributes" to be used in the Model.

- Compare the system attributes using the source documents of the reference tool.
  - o Capture the differences between these agents in a table. These 5 areas, and associated factors, will be used to capture the differences between the systems, and include:
    1. System Attributes (speed)
    2. Protection Attributes (Enemy Ph, Concealment)
    3. Weapons Attributes (Ph)
    4. Secondary Weapons Attributes (Ph)
    5. C4SI (Td, Pc)
  - o The completed assessment of the system differences can be seen below. In this example, we compare an MIA2 to a T80U.

Attribute	Weight	M1A2	T-80U	+/- 5%	Modeled?	Calibrate?
System	0.25	0.17	0.17	0.0%	Yes	No
Protection	0.35	0.38	0.28	26.3%	No	Yes
Weapons	0.35	0.21	0.22	-4.8%	Yes	No
Aux Weap	0.05	0.08	0.05	37.5%	No	No
Inter C4I	N/A	0.25	0.201	19.6%	No	Yes
F.E. x10	1.00	10.90	9.21			

  - o Note: Internal C4I comes from Step A2b (Internal C4I FE), and accounts for roughly 23% of the systems combat power. External C4I will be addressed in the next section (External Dependencies Calibration).
  - o Determine if the model needs to be calibrated to account for them. If the system attributes are equivalent (+/-5%), or are explicitly modeled, then no calibration is needed. If calibration is needed, identify the key combat factors that can be used to calibrate each agent in these areas, less is better. Avoid factors that are known/fixed...like firing rate, number rounds, ect. Only calibrate factors that are not accounted for by the model or quantified by real world data...i.e. only factors that you are using as a baseline for all agents.
  - o Quantify the changes to agent attributes needed to represent the system differences.

    M1A2 are 26.3% more protected than the T-80U, so reduce the T-80s Ph by 26.3% (Weighted by 70% to account for the weapon weight (35%) and the protection weight (35%)) (Main Gun). Because "protection" is not accounted for by MANA in any specific way, this calibration is valid.

    M1A2 Aux Weapons are 37.5% better. If weapons are modeled individually, disregard, validation is not needed. If using a base system for both agents, like a 50 Cal, then calibration is valid, and user should increase the RoF of the M1A2 50 Cal by 37.5%. Because 50 calls are irrelevant in this example, this calibration is not needed.

    M1A2 has 19.6% better sensors, If sensor ranges/Td,Pc are known, disregard, validation is not needed. If using a common base sensor for both agents as in this example, then calibration is valid, and user should increase the Td,Pc of the T-80U by 19.6%. Weight this for the TA-80 status as a Tier 2 system (40% contribution of C4I, 70% of which is internal). Because of the small range of Td, add in a few seconds.

The first half of agent calibration supported the comparison of opposing agents by identifying the difference between the tanks in terms of modeling factors used in the model. Following my comparison of the tank attributes of both the M1A2 and the T-80U

in the FA-SWN, I made a determination on which agent factors I needed to calibrate. Because the system and weapons attributes of both tanks were within +/- 5% of each other, calibration of these factors was not needed. Because auxiliary weapons were not used in this demonstration, that difference did not need to be accounted for either. This left just two factors that were both significant and not being modeled: protection and internal C4I. Thus, the IMDP recommended the calibration of Red P_h(-), T_d(+), and P_c(-) to account for these system level differences. Following system comparison, the next step was to quantify the delta that would need to be applied to each factor; the steps of which can be seen in Table 35.

Table 35. IMDP: A3c-2 (Quantification)

- Modify the model to account for these system differences.
    - Instantiate the table below using the assessments from above. Note, this is a rough assessment, meant to give us a starting point for establishing the bounds of the DOE, it doesn't need to be perfect. So if unsure, error towards a larger design space, the following steps will support the scoping of the range.
    - Note: When selecting a choosing individual factors it is sometimes possible for anomalies in later steps of the calibration to occur. These anomalies, while rare, typically happen when factors are calibrated separately. To avoid such anomalies, the IMDP recommends always calibrating factors in pairs. For example, the previous steps say to reduce Red Ph by 26.3%. The IMDP suggest you do this by splitting the delta, reducing Red Ph by 13.1% and Increasing Blue Ph by 13.1%, then calibrate both factors. This should be done for all factors. For simplicity of this example, I forgo this recommendation because I already know that no anomalies will result.

Factor	Mission Attribute	Cal Modifier	Weight	Agent Attribute	Note	
Blue Agent Speed	30	-	-	30		From Step A3b (Mission)
Red Agent Speed	0	-	-	0		
Blue RoF	12	-	-	0		
Red RoF	26	-	-	0		
Blue Concealment	10	-	-	10		
Red Concealment	65	-	-	65		
Blue Ph (at 3500m)	0.150	-	-	0.150		
Red Ph (at 3500m)	0.400	0.263	0.70	0.326	Main Gun	
Blue Td (4000m)	8.000	-	-	8.000		New (Agent)
Red Td (4000m)	8.000	0.196	0.70	9.098	Veh	
Blue Pc (per det)	0.350	-	-	0.350		
Red Pc (per det)	0.350	0.196	0.80	0.295	Veh	

-
    - Of these factors. Speed, RoF, Conc, and Ph have already been mission calibrated in the model, thus there modification is simple. Because Td and Pc have not been calibrated yet, careful attention will need to be paid to their implementation and selection of settings.

Calibration modifiers for each identified agent factor were transferred into the tool, along with the weight for that source of combat power based on the analysis of the previous step. The tool then recommended a modified bounds for the DOE for each of these agent attributes. Following the quantification of the factor modification, I was able to finalize agent calibration following the steps in Table 36.

Table 36. IMDP: A3c-2 (Bounding)

- Transfer these factor settings and establish appropriate DOE ranges in the table below.
    - The FR ranges will need to be adjusted to maintain the 40% to 95% victory calibration bounding. To do this, use the IRCPAT instantiated at the begging of this step to adjust the number of agents in order to identify the number needed to achieve 40%, 50%, 90%, and 95% victory. For this example, this was 40,43,55,and 59 tanks.
    - "Best" ranges (High or low), should be fixed based on the mission attributes above. I.e., the DOE should not allow values that would increase the capabilities of attributes which we are trying to reduce. The other side (high or low) should use the new agent attribute from above. Because we are not accounting for weighting, we are likely overestimating the impact of these attributes, but the DOE should account for that if property bounded.

	DPs	Factors	Low (40%)	Model	High (95%)
FR Attribute	1	# Blue Tanks	40	43	59
Mission Attribute	2	Red Ph (at 3500m)	0.326	0.350	0.400
Agent Attribute	3	Red Td	8	9	11
	4	Red Pc	0.295	0.325	0.350

As shown in Table 36, I started by adjusting the FR attributes. Because the relative combat power of the Blue tanks increased, the number of tanks had to be reduced to maintain the 40% to 95% P_v trade-space of interest to me. Thus, the range of Blue tanks decreased from 46–83, as used in the mission calibration, to just 40–59. Next, the mission and agent attribute DOE ranges were altered based on the desired impact of the modification. For P_h and P_c, this required a decrease in capability, and thus, I modified the lower bound of the DOE range while fixing the upper bound. For T_d, the opposite was true, and an increase was needed, so I fixed the lower bound and extended the upper bound. With the Agent attributes identified and the DOE ranges established, I executed the DOE following the steps outlined in Table 37.

Table 37. IMDP: A3c-3

3	DOE: Execute a multi-factor DOE of the updated model by varying Force Ratio and any Mission/Agent attributes identified above in order to verify that the model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios after agent calibration.					
	-	Set your Design Points based on the work from above, modifying just the Mission/Agent attributes noted above. Ensure you provide adequate trade space to explore each factor setting.				
		o	Stack 1 (Attack vs. Defense)			
			DPs	Factors	Low	High
		FR Attributes	1	# Blue Tanks	40	59
		Mission Attributes	2	Red Ph (at 3500m)	0.326	0.400
		Agent Attributes	3	Red Td	8	11
			4	Red Pc	0.295	0.350
	-	Select and Build your Design.				
		o	Determine the number of Factors (4 in this example).			
		o	If the number of factors is 13 or less, use a 2nd Order NOLH design. If it is greater than 13 up to 29, use a NOLH design. Both the NOLHdesigns.xlsx and the MacCalman-2ndOrderNOLH design tools can be found at https: //harvest.nps.edu/ .			
		o	Download the DOE tool and input the values from the previous step.			
		o	Consider conducting a screening design to determine significance, this may allow you to reduce the number of factors, and thus, use a more detailed 2nd order design in subsequent analysis.			
	-	Stack the design .				
		o	Stack the design to achieve better resolution within the design space as well as the solution space, which will provide better fitting models. Remember to vary the columns when stacking.			
	-	Execute the DOE.				
		o	For my work I provided the following files to the NPS SEED Center in order to run my model on the advanced computing cluster.			
			1	MANA Model .xml		
			2	The Design developed using the DOE above (translation to the .csv is needed)		
			3	The Study .xml script (this executes the model and design on the cluster)		
	-	The SEED center can assist in preparing these documents for execution if needed.				

As with mission calibration, I chose to use a simpler NOLH design for this demonstration rather than the 2nd order NOLH design the IMDP suggests. To increase the design saturation, I used a nine-factor design rather than a four-factor design, and after stacking nine ties and replicating 100 times, this 33 DP design resulted in a 29,700 DP simulation run. Once the output data was returned, the steps outlined in Table 38 were used to conduct analysis.

Table 38. IMDP: Part A3c-4

4 Conduct analysis of the DOE output in order to establish the Agent Attributes for the HA-HD mission which results in the least variation between the model and the IRCPAT expected Blue Victory % across the full range of potential force ratios.

- For this work, I used JMP to conduct regression analysis, and then used the contour profilers to identify Agent settings for each mission set that kept variation of the mean less than +/-5% from the expected victory based on victory curve #4.
  - o Now that agent differences are now being accounted for, we can no longer use #Blue Tanks/#RedTanks to represent the Force Ratio when creating a FR column in JMP. Thus, we need to us a formula to calculate the actual FR as follows:

	Tanks	FR before	FR now
#Blue Tanks * 10.85	59	2.95	3.48
#RedTanks * 9.20	20		

  - o This difference between FRs captures the system level advantages of the systems being modeled. Otherwise, the analysis is the same as in the last step. These numbers are based on the FE from the reference tool.
- Ranges for analysis should be based on the mission set. Below is the suggested Force Ratio Ranges for each mission set, both bounding and calibration, based on victory curve 4 of the IRCPAT. Again, these will need to be adjusted to account for the new Force Ratios based on Agent attributes. The FRs themselves should remain constant, only the # tanks has changed, to reflect the increased capability of tanks...thus, a smaller number of Blue

	Force Ratios for % Victory			
Mission Set	Bound Low (40%)	Calibrate Low (50%)	Calibrate High	Bound High
HA-HD	2.37	2.50	3.22	3.48

- Ensure that the solution space is saturated. If the output data produced outcomes that heavily favors victory of one side over the other, then the meta-models generated from that analysis will be skewed in that direction. To ensure that this bias is removed, you must ensure the solution space has a nearly equally distribution of outcomes above and below the expected victory curve. A 10% variation (40/60% split) is acceptable, any more and the DOE ranges above will need to be extended in the direction that favors the looser
- Each set of Agent attributes should result in a mean victory of blue forces being within +/-5% of the expected victory curves as described in the IRCPAT across the full range of force ratios ranges (Calibration low to Calibration high) as seen above, while attempting to maintain the relative hierarchy and order of each factor in relation to itself in other mission sets as seen in the table below. Thus, try to limit the number of factors adjusted. In this example, I choose to modify just Red Ph to finalize the calibration, increasing it from 0.257 to 0.345. This is still below the original Mission attribute of 0.4, so this modification just limits the size of the degradation due to agent calibration. Because Ph was the most significant factor, it is easy to see how I simply overestimated the impact of
- Following the analysis and contour profiling exploration, record the Baselined Agent Attributes that minimize the variation between the expected victory of the model and the reference tool across the calibration range of force ratios noted above. These will be used as the baseline factor settings in the model.
- Execute a 1 x factor DOE of the updated model by varying only Force Ratio (#Blue Tanks), from 40 to 59 in this example, and verify that the model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios.
- For more accurate "Agent Attributes" calibration, repeat these steps for other agent types if other agents account for greater than 25% of the total RCP. If not, you can disregard at this point, all other agents will be implicitly calibrated in the operational model during

The purpose of agent calibration analysis is to estimate a set of factor settings that will capture the impacts of the system level differences between the tanks within the model, while maintaining calibration of the model output to the IRCPAT (+/- 5%) across all possible FRs. The first thing I did here was to change how the FR was calculated in my analysis. Previously, when the systems were identical, calculating the FR was simply done by dividing the number of Blue tanks by the number of Red tanks. Now that the systems were no longer equivalent, I modified the calculation by multiplying the number of tanks by their respective FE. Failure to do so would have resulted in flawed analysis. Next, I ensured that the solution space was sufficiently saturated. Figure 61 shows the solution space plot for agent calibration.

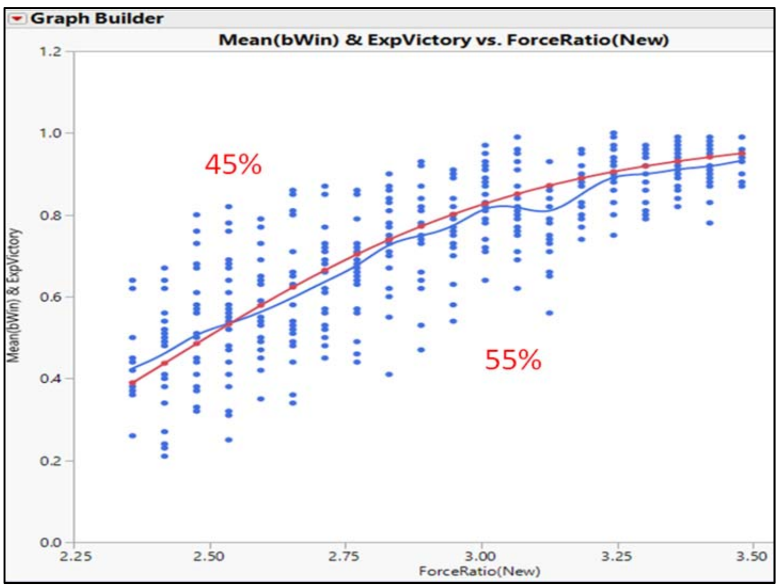


Figure 64. Agent Calibration DOE Solution Space Saturation

As shown in Figure 64, the distribution of the DPs meets the IMDP criteria for being considered saturated, in that the total deviation between the upper and lower distributions about the expected curve is 10% or less. Initially, I did not achieve adequate saturation, and I was forced to iterate my DOE ranges, specifically by expanding the lower bound of Red P_h and the upper bound of Red T_d, until I achieved the saturation

seen in Figure 67. With saturation of the solution space validated, I then used the JMP contour profiler seen in Figure 65 to determine the Agent factors settings.

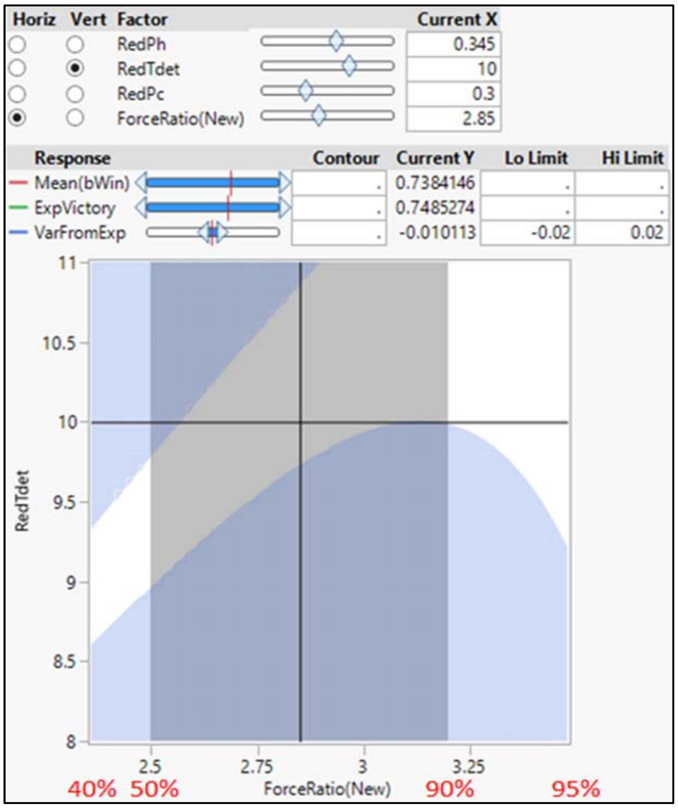


Figure 65. Contour Profiler of Agent Attributes

With these attribute settings, I was able to achieve less than 5% deviation in the P_v between the model and the IRCPAT across all FRs of interest, and less than 2% deviation across most FRs. These attributes capture the system dependent advantages gained from superior systems, and would be used in the future during the development of the final model. Following the calibration, I recorded the agent attributes in Table 39.

Table 39. IMDP: A3c-4 (Results)

	HA	HD
Conc	10	65
Ph	0.15	0.345
RoF	12	26
Speed	*30*	*0*
Pc	0.350	0.300
Td	8	10

With the agent factor settings recorded, my next step was to verify the results by executing a one factor DOE, where I varied the Force Ratio (#Blue Tanks) to verify that the output of the model mirrors the expected results of the IRCPAT across the full range of potential FRs. The results of my analysis can be seen in Figure 66.

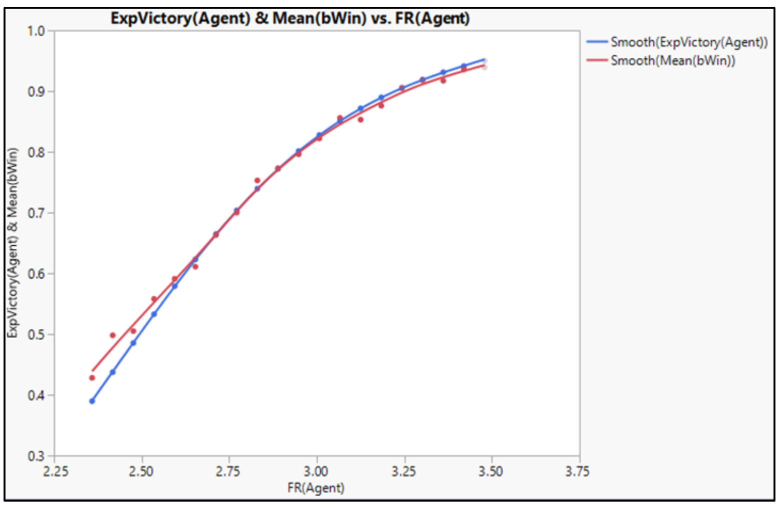


Figure 66. Agent Calibration Verification

My verification DOE confirmed that the agent factor settings identified previously produced nearly identical results in both the model and the IRCPAT. Thus, the model was now calibrated with the reference tool, and capable of producing results that fall within +/- 5% of the IRCPAT across all FRs of interest. With agent calibration completed, I expanded the model to account for the external dependencies of the system.

i. Part A3d: External Dependency Calibration

The intent of this step was to link the model to the IRCPAT through the establishment of attributes that would represent the system level dependencies on external sources for the generation of internal combat power. By calibrating external dependencies I was able to capture the contributions of superior external support sources and structures of opposing forces while maintaining the synchronization of the P_v between the tool and the model. Table 40 outlines the steps of ExtDep calibration.

Table 40. IMDP: Part A3d

1	Update the reference tool by setting the external dependencies of each force to 100%, which will now account for the external dependencies of the system for generating internal combat power.	
2	External Dependency Calibration: Calibrate the ExtDep Attributes for each agent to account for variations in system dependencies on external sources of internal combat power to create the final "ExtDep Attributes" to be used in the Model.	
3	DOE: Execute a multi-factor DOE of the updated model by varying Force Ratio and any ExtDep attribute identified above in order to verify that the model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios after ExtDep calibration.	
4	Analysis: Conduct analysis to establish the baseline ExtDep factor settings.	
	-	Trade-space exploration to minimizing variation from expected outcomes.
	-	Record the Calibrated ExtDep Attributes as factor settings for use in the model.

I began ExtDep calibration by expanding the IRCPAT to account for the external dependencies of the M1A2 and the T-80U. Specifically, I set the status of external C4I to 100% for both forces. Then, I updated the number of Blue tanks to maintain the P_v of the Blue force at 50%. My expanded IRCPAT can be seen in Figure 67.

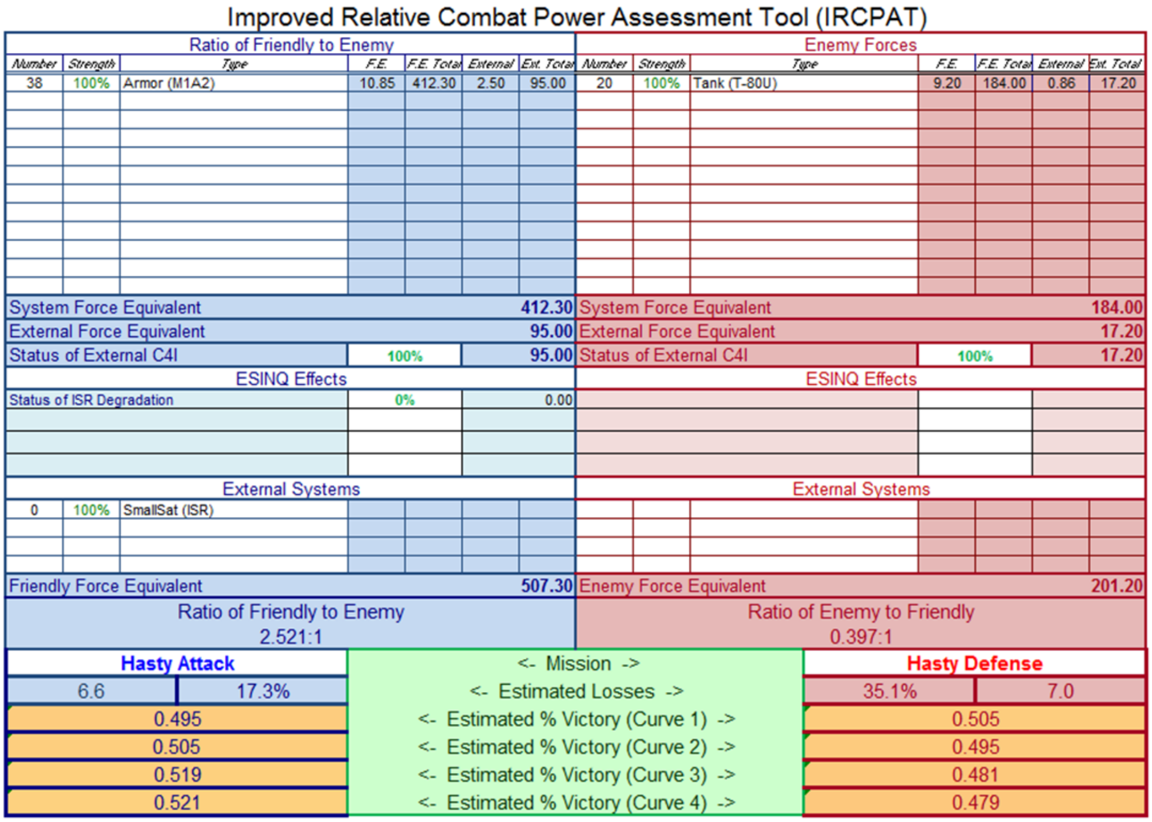


Figure 67. IRCPAT (ExtDep Calibration)

As shown in Figure 67, the IRCPAT was updated to account for the system level dependencies on external support for the generation of internal combat power. Thus, because of the greater contribution from external sources for the M1A2 compared to the T-80U, a significant shift in the RCP was seen, which increased the expected Blue P_v from 53% to roughly 75%. I took advantage of this increased RCP by decreasing the number of Blue tanks needed to maintain the Blue P_v at 50%, which resulted in a decrease from 43 to just 38 tanks. Following the expansion of the IRCPAT, the IMDP directed me to execute ExtDep attribute calibration, starting with the comparison of the external dependencies of the opposing systems, the steps of which are described in Table 41.

Table 41. IMDP: A3d-2 (ExtDep Comparison)

2 External Dependency Calibration: Calibrate the final ExtDep attributes to identify the steady state settings for these factors (to include the contributions from external dependencies on internal metrics of combat power) that cause no disruption to the outcomes of the model and reference tool. These will act as the reference from which future manipulation of these factors will be made.

- At this point, the model (w/o ext dependencies) matches the IRCPAT (w/o ext dependencies), thus, we have baselined the IRCPAT and model for system level combat power. Now we must account for the systems internal dependencies on external contributions to combat power. This is already done in the IRCPAT, but now we must calibrate the model to the IRCPAT, this time for external dependencies.
- Copy the calibration attributes ranges from step A3c here.

	Base Line (0% Ext Cont)		Expanded (100% Ext Cont)	
	HA	HD	HA	HD
Conc	10	65	?	
Ph	0.15	0.345		
RoF	12	26		
Speed	30	0		
Pc	0.350	0.300		
Td	8	10		

  - o These base line attribute values will represent the worse case scenario (0% contribution to internal combat power in the model from external sources) The goal of this step is to figure out the best case scenario (100% contribution).
- Insert the FE and Ext dependencies for the agent being calibrated from part A2b.

	FE	ext	tot	%
M1A2	10.85	2.5	13.35	**0.187**
TA-80U	9.2	0.86	10.06	**0.085**

  - o The increase to combat power of both forces will need to be accounted for in the model to represent the contribution from external sources. Thus, we will need to modify the baseline calibration attributes to account for this increase in combat power, and then use these new values as the 100% external contributions to internal combat power. The difference between these two sets of values will drive the meta-models used to represent the impacts from internal dependencies on external sources of combat power in the model.

This first part of ExtDep calibration supported the comparison of opposing agents by identifying the dependencies of the tanks on external sources for the generation of combat power. By determining the percentage of total combat power for each tank derived external to the system boundary, I was able to estimate a general modification factor that could be used on specific agent attributes in the model to increase the overall effectiveness of both tanks due to the contributions from external sources. Following ExtDep comparison, the next step focused on identifying the mission and agent factors that would be modified to represent this increase in system level combat power, the steps of which can be seen in Table 42.

Table 42. IMDP: A3d-2 (ExtDep Attribute Selection)

- Identify the attributes from above that can be used to represent the contributions from eternal systems on internal combat power. Because external dependencies revolve mostly around C4I, I would suggest attributes that would likely be impacted by it.

C4I Attributes:	~~Conc~~	Ph	~~RoF~~	~~Speed~~	Pc	Td

  - o Because one force is likely stationary, speed is not very useful.
  - o Because Td is currently set at 8/10 sec respectively, it is limited on the low end, and thus does not have much room for improvement, and thus, is likely just a secondary factor at best.
  - o Pc has strong ties to C4I, and a lot of wiggle room, thus, is a good primary factor for calibration.
  - o While Ph is not directly impacted by C4I, it is indirectly, and thus a usable modifier if the other factors don’t have enough power to make the required changes, to be safe, include it in the DOE for now, but try to minimize changes.

As shown in Table 42, I conducted a logical inspection of the potential factors that could be modified to represent the desired impacts from the application of external dependencies for the tanks. Following my assessment, I determined that P_h, T_d, and P_c were all potential candidates, but decided that T_d and P_c were more appropriate with regard to C4I, and should have more than enough flexibility in their ranges to capture the impacts which I was interested in representing in the model. Thus, I transferred these two factors along with the corresponding attribute values into the tool provided by the IMDP described in Table 43.

Table 43. IMDP: A3d-2 (Bounding)

- Transfer these factors and the Agent attribute values for each in to the format below. The tool will produce a DOE range for the calibration of external contributions to internal combat power. Note, depending on the direction of improvement, the high or low of each attribute will remained fixed at the baseline values, this will ensure that no improvement will cause a reduction in capabilities.

Factor	Agent Attribute	Cal Modifier	ExtDep Attribute	DOE Low	Model	DOE High
Blue Ph (3500m)	0.150	0.187	0.178	0.150	0.178	0.206
Red Ph (3500m)	0.345	0.085	0.374	0.345	0.374	0.404
Blue Td (4000m)	8	0.187	6.502	4	6	8
Red Td (4000m)	10	0.085	9.145	8	9	10
Blue Pc (per det)	0.350	0.187	0.416	0.350	0.416	0.481
Red Pc (per det)	0.300	0.085	0.326	0.300	0.326	0.351

- Note: As we saw in Agent calibration, the IMDP recommends that all factors be calibrated in pairs, as shown here. Additionally, ExtDep calibration must take place on factors that have already been calibrated in either mission or agent calibration, attempting to calibrate factors in this step that have not been calibrated previously risk introducing anomalies in the resulting meta-models. Thus, for this example, I am limited to the use of just Red Ph, Td, and Pc. Because I believe that the use of Ph is unnecessary to capture the impacts that I am looking to represent, I will not be using it. Thus, the demonstration table looks like this.

Factor	Agent Attribute	Cal Modifier	ExtDep Attribute	DOE Low	Model	DOE High
Red Td (4000m)	10	-0.102	11.020	10	11	14
Red Pc (per det)	0.300	-0.102	0.269	0.208	0.269	0.300

- Because I am just modify the red attributes from Agent calibration (Red Td and Pc) in this example (which is purely for demonstration purposes), I will need to take the difference between the ExtDep of both systems, and apply it to the Red force. In this case, an overall increase of 0.102 to blue combat power is expected. Thus, by applying this as a negative modifier to red Td and Pc, we can achieve the desired differential. While this will not allow us to independently modify Blue or Red dependencies on ExtDep, for this demonstration it is sufficient, and will demonstrate the dependence of both forces on external sources of combat power as long as that dependency scales equally.
- As before, the FR ranges will need to be adjusted to maintain the 40% to 95% victory calibration bounding. To do this, use the IRCPAT instantiated at the begging of this step to adjust the number of agents (Blue Tanks) in order to identify the number needed to achieve 40%, 50%, 90%, and 95% victory. For this example, this was 36, 38, 49, and 53 tanks.

While the IMDP recommended the use of six factors to represent external dependencies of the opposing forces, the approach I took with this demonstration allowed me to use just two. To identify the ExtDep attribute DOE ranges needed to achieve the desired relative improvements to Blue P_v due to external dependencies, T_d and P_c of the Red force would need to be decreased. To do this I fixed of one side of the DOE range for each factor using the current attribute settings, and used the tool provided by the IMDP to establish the other bound. Next, to account for the increase in Blue combat power due to the superior application of external sources of combat power, I reduced the

number of Blue tanks to maintain the 40% to 95% P_v trade-space of interest to me. Thus, I was able to reduce the number of Blue tanks needed in the DOE from 40–59 as used in the agent calibration, to just 36–53. With the ExtDep attributes identified, FR determined, and the DOE ranges established, I executed the DOE as outlined in Table 44.

Table 44. IMDP: A3d-3

3	DOE: Execute a multi-factor DOE of the updated calibration model by varying Force Ratio and the ExtDep attributes identified above in order to verify that the updated model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios.						
	-	Set your Design Points based on the work from above, modifying just the ExtDep attributes noted above. Ensure you provide adequate trade space to explore each factor setting.					
		o	Stack 1 (Attack vs. Defense)				
				DPs	Factors	Low	High
			FR Attributes	1	# Blue Tanks	36	53
			ExtDep Attributes	2	Blue Ph (3500m)	0.15	0.206
				3	Red Ph (3500m)	0.345	0.404
				4	Blue Td (4000m)	4	8
				5	Red Td (4000m)	8	10
				6	Blue Pc (per det)	0.350	0.481
				7	Red Pc (per det)	0.300	0.351
		o	For this demonstration, the following simplified design was used.				
			FR Attributes	1	# Blue Tanks	36	53
			ExtDep Attributes	2	Red Td (4000m)	10	14
				3	Red Pc (per det)	0.208	0.300
	-	Select and Build your Design					
		o	Determine the number of Factors (3 in this example)				
		o	If the number of factors is 13 or less, use a 2nd Order NOLH design. If it is greater than 13 up to 29, use a NOLH design. Both the NOLHdesigns.xlsx and the MacCalman-2ndOrderNOLH design tools can be found at https: //harvest.nps.edu/				
		o	Download the DOE tool and input the values from the previous step				
		o	Consider conducting a screening design to determine significance, this may allow you to reduce the number of factors, and thus, use a more detailed 2nd order design in subsequent analysis.				
	-	Stack the design					
		o	Stack the design to achieve better resolution within the design space as well as the solution space, which will provide better fitting models. Remember to vary the columns when stacking.				
	-	Execute the DOE					
	-	o	For my work I provided the following files to the NPS SEED Center in order to run my model on the advanced computing cluster.				
			1	MANA Calibration Model .xml			
			2	The Design developed using the DOE above (translation to the .csv is needed)			
			3	The Study .xml script (this executes the model and design on the cluster)			
	-	The SEED center can assist in preparing these documents for execution if needed.					

As with agent calibration, I chose to use a simpler NOLH design for this demonstration rather than the 2nd order NOLH design the IMDP suggests. To increase

saturation I used a nine-factor design, and after stacking nine times and replicating 100 times, the 33 DP design resulted in a 29,700 DP simulation run. Once the output data was returned, I used the steps outlined in Table 45 to conduct analysis.

Table 45. IMDP: Part A3d-4

4	Conduct analysis of the DOE output in order to establish the modifications to the calibration attributes needed to represent the impacts from internal dependencies on external contributors to combat power, which results in the least variation between the model and the IRCPAT expected Blue Victory % across the full range of potential force ratios.		
	-	For this work, I used JMP to conduct regression analysis, and then used the contour profilers to identify modified calibration attributes settings for each ExtDep factor that kept variation of the mean less than +/-5% from the expected victory based on the IRCPAT victory curve #4.	
		o	Now that ExtDep are now being accounted for, we can no longer use the previous FR formula to represent the Force Ratio when creating a FR column in JMP. Thus, we need to us a formula to calculate the actual FR as follows:

Formula	Tanks	FR before	FR now
#Blue Tanks * (10.85 + 2.50)	53	3.13	3.52
#RedTanks * (9.20 + 0.86)	20		

		o	This difference between FRs captures the system level advantages of the systems being modeled. Otherwise, the analysis is the same as in the last step. These numbers are based on the FE from the reference tool.
	-	Ranges for analysis should be based on the mission set. Below is the suggested Force Ratio Ranges for each mission set, both bounding and calibration, based on victory curve 4 of the IRCPAT. Again, these will need to be adjusted to account for the new Force Ratios based on ExtDep attributes. The FRs themselves should remain constant, only the # tanks has changed, to reflect the increased capability of tanks...thus, a smaller number of Blue Tanks can achieve the same FR as previously.	

	Force Ratios for % Victory			
Mission Set	Bound Low (40%)	Calibrate Low (50%)	Calibrate High (90%)	Bound High (95%)
HA-HD	2.37	2.50	3.22	3.48

	-	Ensure that the solution space is saturated. If the output data produced outcomes that heavily favors victory of one side over the other, then the meta-models generated from that analysis will be skewed in that direction. To ensure that this bias is removed, you must ensure the solution space has a nearly equally distribution of outcomes above and below the expected victory curve. A 10% variation (40/60% split) is acceptable, any more and the DOE ranges above will need to be extended in the direction that favors the looser (without exceeding original Max calibration Attributes). This is an iterative process.
	-	Each set of calibration attributes should result in a mean victory of blue forces being within +/- 5% of the expected victory curves as described in the IRCPAT across the full range of force ratios ranges (Calibration low to Calibration high) as seen above. Ensure that the analysis includes the external dependencies that have up until this step been ignored in the IRCPAT and analysis. This will require an updated Force Ratio formula as well as the updated IRCPAT.
	-	Following the analysis and contour profiling exploration, record the Expanded calibration Attributes that will be used to account for the external dependencies of the system that minimize the variation between the expected victory of the model and the reference tool across the calibration range of force
	-	Execute a 1 x factor DOE of the updated calibration model (ExtDep expansion) by varying only Force Ratio (#BlueTanks), and verify that the updated model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios. This will represent your 100% External dependencies data source for meta-model development.
	-	For more accurate "ExtDep Attributes" calibration, repeat these steps for other mission sets. While this is may not be necessary, if the time is available, it is advised.

The purpose of ExtDep calibration analysis was to estimate a set of factor settings that can represent the impacts of the system level dependencies on external sources for

the generation of internal combat power, while maintaining the models calibration to the IRCPAT (+/- 5%) across all FRs. The first thing I needed to do here was to change how FR was calculated in my analysis. I did this by modifying the formula for calculating FR by including external dependencies into the tank FE prior to its multiplication with the number of tanks. Next, I ensured that the solution space was sufficiently saturated, the plot for which can be seen in Figure 68.

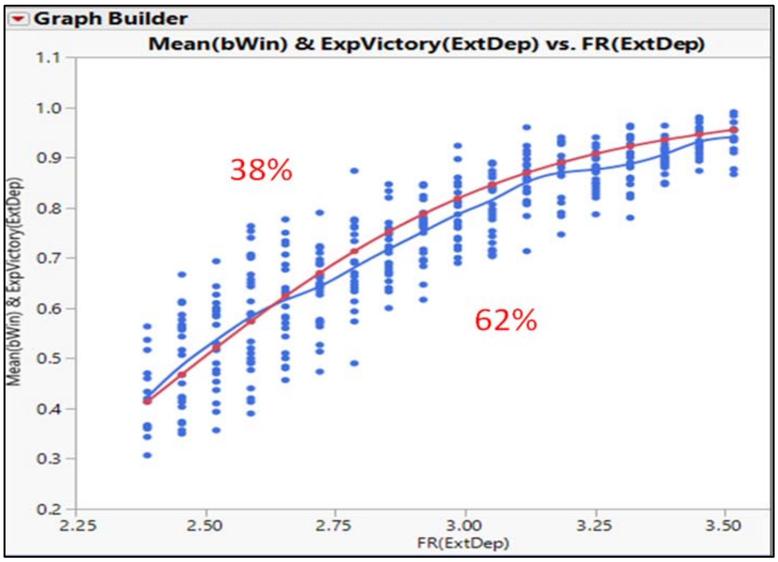


Figure 68. ExtDep Calibration DOE Solution Space Saturation

As shown in Figure 68, the distribution of the DPs did not quite meet the IMDP criteria for being considered saturated because the total deviation between the upper and lower distributions about the expected curve was 12%, 2% greater than required. Regardless, I felt that it was close enough for this demonstration for use, and as long as the DOE and the verification supported that claim it would be acceptable. Following my tentative assessment of a saturated solution space, I determined the settings of the ExtDep factors settings by using JMP, the contour profiler for which can be seen in Figure 69.

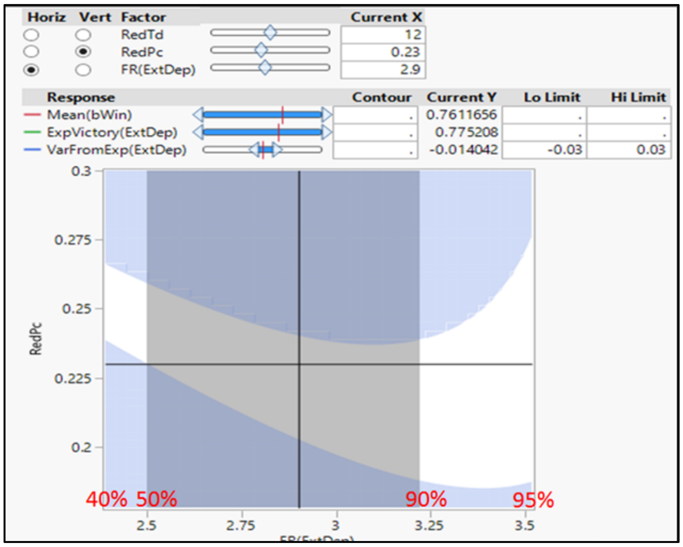


Figure 69. Contour Profiler of ExtDep Attributes

Using the two ExtDep attribute settings shown here, I was able to achieve a less than 3% deviation between the P_v of the model and the IRCPAT across all FRs of interest. Thus, using these factor settings, the model should now be calibrated to the reference tool, and produce results that will fall within +/-5% of the results of the IRCPAT. These settings were then recorded in Table 46.

Table 46. IMDP: A3dc-4 (Results)

	Base Line (0% Ext Cont)			Expanded (100% Ext Cor	
	HA	HD		HA	HD
Conc	10	65		N/C	N/C
Ph	0.15	0.345		N/C	N/C
RoF	12	26		N/C	N/C
Speed	30	0		N/C	N/C
Pc	0.350	0.300		N/C	0.230
Td	8	10		N/C	12

These factor settings capture the relative dependency of the opposing forces on eternal sources for the generation of internal combat power, and will be used in the future during the development of the final model. Because I chose to use a simplified demonstration of the IMDP, I was only able to capture the relative impacts of external contributions to internal combat power on the model. Thus, while I was able to modify

the contribution from 0 to 100% for both forces while accurately representing the impacts that external dependencies had on the forces, I could not do so independently. To do so, I should have executed the IMDP as indented, not as I did for this simplified demonstration which was intended to minimize resources and complexity. While this was not optimal, because my decision saved significant time and effort, I believed it was more than justified. With the ExtDep factor settings recorded, the next step was to verify the results by executing a one factor DOE, where I varied the number of Blue tanks to verify that the P_v of the model mirrors that of the IRCPAT across the full range of potential FRs. The results of my analysis can be seen in Figure 70.

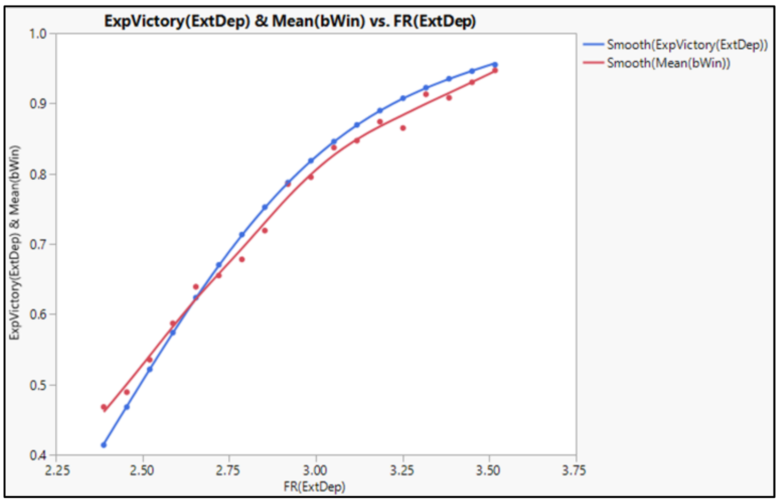


Figure 70. ExtDep Calibration Verification

As shown in Figure 70, my verification DOE confirmed that the ExtDep factor settings identified previously produced nearly identical results between the model and the IRCPAT. Thus, the model was now ExtDep calibrated with the reference tool, and capable of producing similar results (+/- 5%) as the IRCPAT across all FRs of interest. With ExtDep calibration complete, I was able to improve the model further by accounting for the contributions from the ESINQ factors of interest.

j. *Part A3e: ESINQ Calibration*

The intent of this step was to calibrate any ESINQ factors of interest that were not previously calibration during mission, agent, or external dependency calibration. Unlike previous calibration steps, the purpose here was not to establish calibration values, because ESINQ values were established during baseline activities. During this step, the focus was on validating the ESINQ values that had already been used in the calibration process. Table 47 outlines the steps I used for ESINQ calibration.

Table 47. IMDP: Part A3e

1	ESINQ Calibration: Calibrate the ESINQ Attributes to identify the steady state settings for these factors that cause no disruption to the outcomes of the model and reference tool. These will act as the reference from which future manipulation of these factors to implement ENSIQ effects will be made.
2	DOE: Execute a multi-factor DOE of the updated model by varying Force Ratio and any ESINQ attribute identified above in order to verify that the model continues to have a good fit with the expected outcomes predicted by the reference tool across all potential Force Ratios after agent calibration.
3	Analysis: Conduct analysis to establish the baseline ESINQ factor settings. - Trade-space exploration to minimizing variation from expected outcomes. - Record the Calibrated ESINQ Attributes as factor settings for use in the model.

Unlike previous calibration steps, there was no need to start this step by updating the IRCPAT. The IRCPAT cannot address ESINQ factors, though at the conclusion of this demonstration I will have the meta-models necessary to do so. This application of the IMDP is outside of the scope of this demonstration, but will be discussed in Chapter V: Application. Thus, I began ESINQ calibration by determining which ESINQ factors still required calibration, the steps of which were found in Table 48.

Table 48. IMDP: A3e-1 (ESINQ Calibration Assessment)

1 ESINQ Calibration: Calibrate the ESINQ Attributes to identify the steady state settings for these factors that cause no disruption to the outcomes of the model and reference tool. These will act as the reference from which future manipulation of these factors to implement ENSIQ effects will be made in Part B.

- Copy the ESINQ Attributes identified from the EEMM Step A1c here. ** For demonstration reasons, I added in a few extra ESINQ effects to fully explain the process.

	Input Factor	Mission	Agent	ExtDep	Calibrate?	Dependent
	Ave Det Time (sec)		Yes	Yes	No	Yes
	Prob Classification (%)		Yes	Yes	No	Yes
**	Latency (sec)				Yes	No
**	Reliability (%)				Yes	No
**	Ph per Discharge (%)	Yes	Yes		No	Yes

o Disregard any factors that have already been captured in mission, agent, or ExtDep calibration. In this example, this includes:

Mission Calibration:	Ph
Agent Calibration:	Ph, Td, Pc
ExtDep Calibration:	Td, Pc

o Assess the system dependency on the ESINQ effect. For direct fire systems, with shooting based on Agent/squad SA, they can see the target and have limited dependencies on latency and reliability. For indirect systems, which shoot based on inorganic SA, are not as much effected by Td or Speed, but are heavily dependent on Latency and reliability and its impact to Ph.

o If all ESINQ factors are accounted for in either Mission, Agent, or ExtDep calibration, or not necessary due to lack of dependency, this step is not necessary, all ESINQ factors have already been calibrated for steady state, and the user can move on to the next step.

o In this example, an M1A2 is a direct fire system, and thus, not sufficiently dependent on Latency or reliability, and thus, these factors would not need to be calibrated. To keep this demonstration moving forward, lets pretend we are looking at an indirect fire system instead. Thus, calibration of Latency and reliability would need to be done.

This first part of ESINQ calibration supported the assessment of the calibration status of all ESINQ effects. Because I made earlier assessments for the values of the ESINQ effects, my only requirement during ESINQ calibration was to ensure that all ESINQ factors had been calibrated. To do this validation, I assessed the calibration status of the two remaining ESINQ surrogate factors following the execution of the EEMM, which included T_d and P_c. Of these, both T_d and P_c were calibrated during agent and ExtDep calibration. Thus, both ESINQ factors had been calibrated implicitly during the previous calibration processes, and according to the IMDP, no further action was needed. Had there been an ESINQ surrogate factor that had not been previously calibrated, the IMDP would have directed me to calibrate that factor similarly to previous calibration steps, to include bounding of the factor ranges, DOE, analysis, and verification. An example of the full process can be found in the IMDP. With calibration complete, I

recorded the final baseline and ExtDep calibration values for use during the build of the final model, as shown in Table 49.

Table 49. Final Calibration Values

	Base Line (0% Ext Cont)			Expanded (100% Ext Cor	
	HA	HD		HA	HD
Conc	10	65		N/C	N/C
Ph	0.15	0.345		N/C	N/C
RoF	12	26		N/C	N/C
Speed	30	0		N/C	N/C
Pc	0.350	0.300		N/C	0.230
Td	8	10		N/C	12

These calibration values would be used in the model to capture the specific mission, agent, external dependencies, and ESINQ effects (0% impact) while ensuring consistent outcomes between the IRCPAT and the model, across all potential mission sets and FRs. The only values to be modified after this point are the ESINQ effects, and from that modification I would be able to quantify the impacts that they would have on the Blue P_v, which will be discussed in the next section.

The end state of the calibration steps of the IMDP produced a model that could account for the advantageous of the specific mission, agent attributes, external dependencies, and ESINQ effects without introducing any new factors. By simply calibrating agent attributes in the model that already exist; it was possible to implicitly model effects of interest without inducing additional model complexity. This is best described by comparing all three verification plots, as seen in Figure 71.

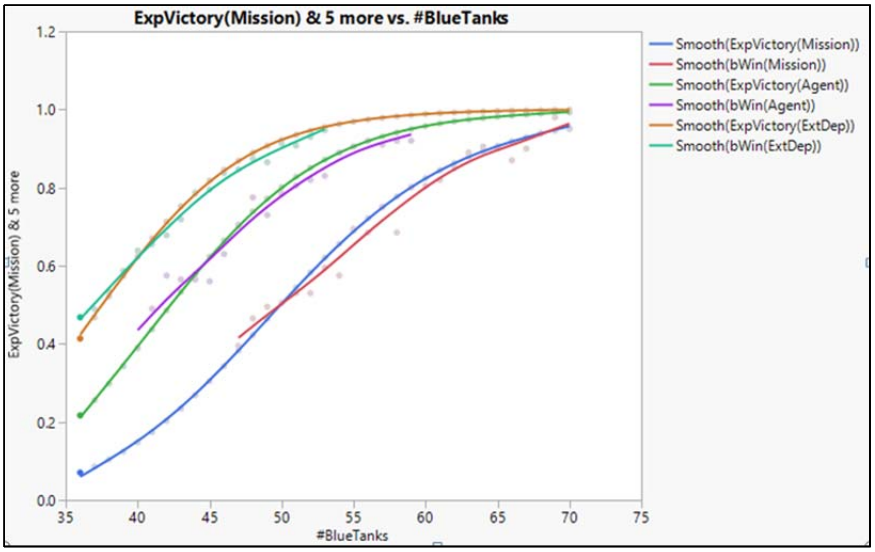


Figure 71. IMDP Calibration Verification Curves

As shown in Figure 71, as I progressed through the calibration process, I gradually increased the capacity of the model to represent the actual OE. As this accuracy was increased, a better understanding of the OE was gained, and thus, a better assessment of RCP was achieved. As shown in Figure 71, as I progress through mission, agent, and finally external dependencies calibration, the number of blue tanks needed to achieve the same P_v decreased. Thus, through implicit modeling, I was able to develop a more accurate model and IRCPAT that were capable of accounting for factors that were previously ignored or aggregated. This reduced the overestimation of combat forces needed to achieve a specific P_v, which has become a systemic issue with modern operational planning. For example, in this example and only considering external dependencies, I was able to determine that the FRC, which is the primary operational planning tool of the Army, was overestimating the number of tanks required to achieve a specific P_v by roughly 11%. But this was just the beginning, now that I had established a stable reference point between the model and the IRCPAT, I was able to introduce ESINQ effects into the model and provide a quantifiable assessment of their impacts on metrics of combat effectiveness, which would further refine the RCP of Blue forces.

2. Part B: Model Development

Part B of the IMDP expands the capabilities of current MDPs and MBSE analysis methodologies by providing users an improved methodology for producing more accurate models using the calibrated data from part A. The purpose of model development is to finalize the implementation of the simplified model used during part A, and then to expand that model to highlight the impacts from the ESINQ factors of interest on metrics of operational effectiveness. Part B of the IMDP does this through the formalized realization and manipulation of the model, with the goal of quantifying the impacts from ESINQ effects on operational effectiveness. The four sub parts of part B will be executed in order to address the scenario described at the begging of this chapter, beginning with model development, where we finalize the model, expand the model to include the ESINQ effects, then conduct DOE, analysis, and then quantifying the ESINQ effects.

a. Part B1a: Model Development

The intent of this step was to finalize the development of the model to mirror the full operational scenario of interest, accounting for all requirements, specifically the ones not addressed during the build of the simplified model in part A. For this demonstration, the ignored aspects of the model focused on the additional forces as outlined in the OC established during part A1c, which included the artillery for both forces. To update the model to include these agents, I executed the 2-step framework shown in Table 50 for each additional agent type.

Table 50. IMDP: Part B1a

1	Model Development: Iterative model development, analysis, and verification.	
	-	Model Development.
2	Implicit Calibration.	
	-	DOE.
	-	Implicit Calibration Analysis and verification.
3	Model analysis and verification.	
	-	Model analysis: collect summary statistics.
	-	Model verification.

During the first iteration of this step, I finalized the development of the simplified model and then updated it to include the opposing artillery systems, which were the next most significant force pair as noted in the IRCPAT established in part A3a1. These systems included six M260A (Multiple Launch Rocket Systems) for the Blue force, and six 9P140 (220mm) for the Red force. I implemented them as outlined by my OC, and used the most accurate information available on their individual performances based on open sources as well as the FA-SWN. The only exception was that I used the baseline Mission, Agent, ExtDep, and ESINQ factor setting established during calibration and modified artillery speed to account for artillery employment techniques, which enforces fairly strict movement protocols. Next, I established all doctrinal communications and sensor links necessary for the artillery to perform its mission. Following my update, I iteratively developed the opposing artillery systems within the model by modifying Blue burst radius until a 100 replication run of the model resulted in a mean Blue P_v that was +/- 5% from the IRCPAT; the analysis of which can be seen in Figure 72.

100	-1.9E+09	21	26
# MultiR	2/6/2017	#######	
Mean		34.39	23.03
StDev		6.86654	4.43916
	Blue Pv	67	

	Blue Tank	Red Tanks	Blue HQ	Red HQ	Blue Arty	Red Arty	**Killer totals**
Blue Tanks	0.0	16.8	0.0	0.0	0.0	0.9	**17.7**
Red Tanks	32.2	0.0	0.0	0.0	0.0	0.0	**32.2**
Blue HQ	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Red HQ	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Blue Arty	0.0	0.7	0.0	0.0	0.0	4.7	**5.3**
Red Arty	2.2	0.0	0.0	0.0	0.0	0.0	**2.2**
Victim totals	**34.4**	**17.4**	**0.0**	**0.0**	**0.0**	**5.6**	**57.4**

Figure 72. IMDP: Part B1a-1 (Artillery Implicit Calibration)

As shown in Figure 72, the mean Blue P_v was 67.0%, just 1.5% from the 65.5% predicted by the IRCPAT, and well within the +/- 5% needed for initial verification. Likewise, the artillery response in the killer-victim spreadsheet was appropriate for the opposing artillery missions, with Red artillery focusing on delaying approaching tanks and the Blue artillery focusing on the destroying enemy artillery. Thus, from my

perspective the behavior of the artillery in the model seemed appropriate, and thus, I considered the models initial verification for artillery complete, and I moved on to implicit calibration.

I started implicit calibration by identifying the surrogate factors I would need to modify. Unlike previous calibration steps, implicit calibration was simpler because I took advantage of the fact that the majority of the combat power of the model had already been accounted for during tank calibration. Thus, the addition of other forces, like the artillery, would have far less impact on the outcomes of the model, which allowed me to calibrate the artillery through the use of just a few surrogate factors while maintaining synchronization with the IRCPAT. As the IMDP directs, I kept this simple and chose just three factors for the re-calibration of the model to account for the addition of the Blue and Red artillery. These factors included the Ph at max range for Blue and Red, as well as concealment for Red in the firing state. Next, to account for the change in FR due to the addition of artillery, I updated the FR ranges to maintain the 40% to 95% P_v calibration bounding, which yielded a slight increase in the number of tanks (37-56) due to the reduction in the overall RCP of the Blue force following the addition of the Artillery. With FR range established and implicit calibration factors identified, the next step was to establish the bounds of the DOE, which I did by using the DOE range tool provided by the IMDP; the results of which can be seen in Table 51.

Table 51. Implicit Calibration DOE Tool (Artillery)

Factor	Agent Attribute	Cal Modifier	DOE Low	DOE High
#Blue Tanks	N/A	N/A	37	56
BlueArtyPh @	0.60	0.12	0.49	0.64
RedArtyPh @ M	0.55	0.15	0.51	0.67
RedArtyConc (	80	0.15	74	98

As shown in Table 51, after I transferred the estimated P_h of the opposing systems into the agent attribute column, I calculate the contributions of each force with respect to the RCP of the overall force, and then applied this percentage to the calibration modifier column. Using this input, the tool calculated a reasonable DOE range for each of the

three agent factors. With the implicit calibration ranges established, I was able to execute a multi-factor DOE following the same steps as outlined in part A3b-e (Calibration), which for this demonstration resulted in an eleven-factor NOLH design (33DPs). After I stacked the design eleven times and replicated 250 times, the resulting design had a total of 90,750 DPs. Once the output was returned, I conducted analysis to identify the values for the three agent attributes that ensured the model was still calibrated (+/- 5%) to the IRCPAT. To do this, I began as I had during part A, by first updating the FR to account for the FE of the artillery, and then verified that the solution space was saturated. The results of this analysis can be seen in Figure 73.

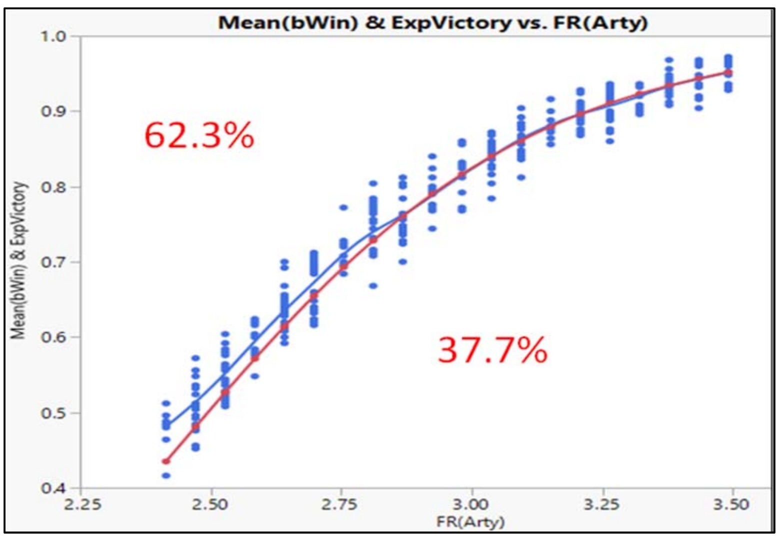
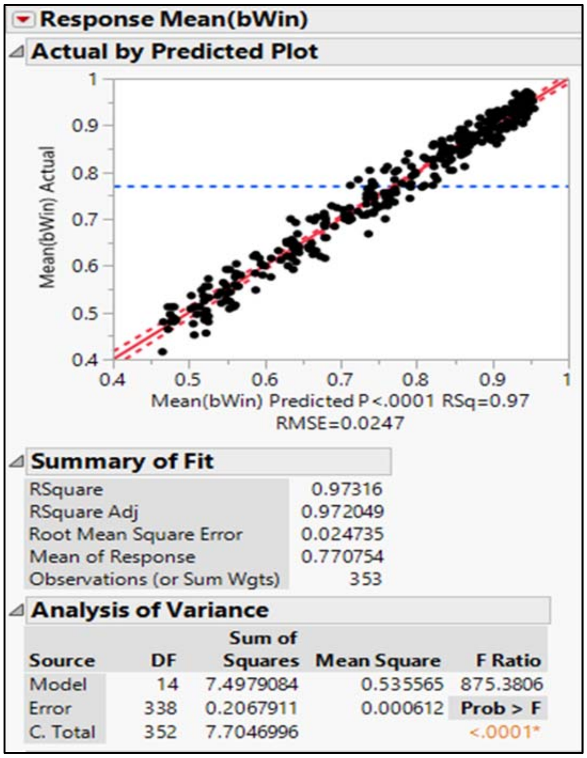


Figure 73. Artillery Implicit Calibration (Solution Space Saturation)

Based on the definition of a saturated solution space described in Chapter II and III, my analysis of the implicit calibration DOE results suggested that the solution space is not saturated, deviating by just 2.3% from the desired 60%/40% split. Though the IMDP directs further modification to the DOE ranges to achieve a less than 10% deviation in distribution about the expected victory curve, because of the tightness of the DPs about the curve, I am confident that this saturation will be sufficient enough to proceed, and as long as no issues arise during the one factor verification this

simplification should be acceptable. Following this test I moved onto regression analysis using JMP, the results of which can be seen in Figure 74.



Summary of Fit

RSquare	0.97316
RSquare Adj	0.972049
Root Mean Square Error	0.024735
Mean of Response	0.770754
Observations (or Sum Wgts)	353

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	7.4979084	0.535565	875.3806
Error	338	0.2067911	0.000612	Prob > F
C. Total	352	7.7046996		<.0001*

Figure 74. Artillery Implicit Calibration (Regression Analysis)

The analysis suggests that the model has an excellent fit, with an adjusted R^2 of 0.97, and the ANOVA showing high confidence in its validity. Red concealment was determined to be insignificant when compared to FR, which dominates the response, and thus would not be modified from their base values during the implicit calibration of the artillery. While both Blue and Red P_h were significant, they were only marginally so, with Blue P_h being the dominate factor of the two. Thus, to simplify the calibration process, I will focus on the modification of Blue $P_{h.}$ TSE was then conducted using JMP contour profilers, which can be seen in Figure 75.

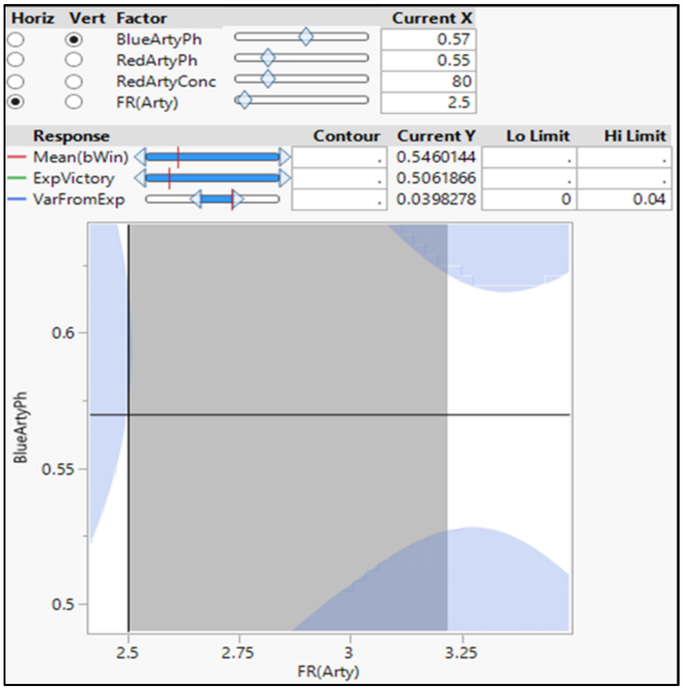


Figure 75. Artillery Implicit Calibration (Contour Profiler)

As shown in Figure 75, while maintaining Red P_h and Red Concealment at their base values, I was able to explore the tradespace and identify a Blue P_h that minimized variation from the expected victory curve, which called for modifying Blue P_h from its base value of 0.60 to 0.57. Thus, with these settings, the model, which now included opposing artillery forces, should maintain its calibration with the IRCPAT (+/- 5%) across all FRs of interest (2.50 to 3.22), denoting the range between 50% and 90% P_v. To verify, I executed a one factor DOE (1000 replications per DP) where the number of Blue tanks was varied from 37 to 56, the results of which are shown in Figure 76.

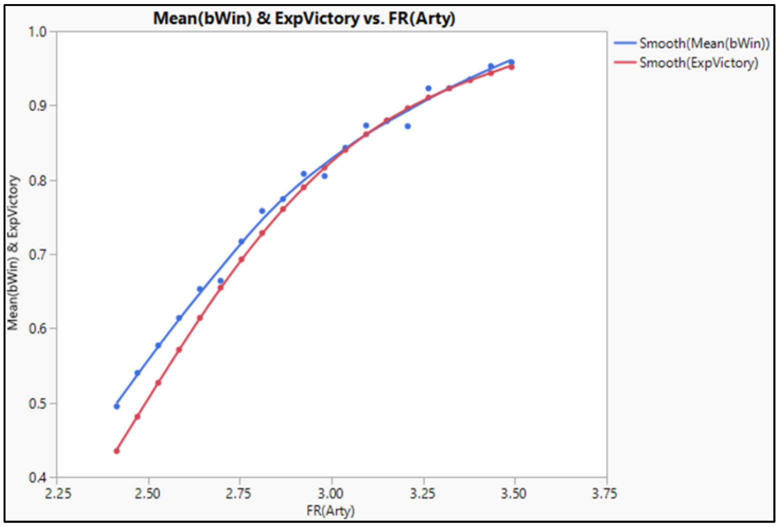


Figure 76. Artillery Implicit Calibration (One Factor Verification)

Following implicit calibration of the artillery systems, my analysis of the one factor DOE results uncovered two artifacts that I was forced to address. First, was the fact that the mean P_v curve was consistently above the expected victory curve. A better distribution of P_v about the expected victory curve would have been more ideal. Second, there were three P_v outliers, the first two were below the 2.50 FR, and thus ignored, while the third, seen at a FR of 2.53, failed to meet the +/- 5% variation from the expected victory curve required by the IMDP for calibration. Thus, the IMDP recommended re-calibration to address these issues, specifically by going back and decreasing Blue Arty P_h from 0.57 to 0.55 and re-doing the verification run. Nonetheless, because this one point was just outside the calibration range (5.02%), and because this was just a demonstration, I felt it was close enough to continue on without re-calibration, although the recommended changes to Blue Arty P_h were implemented. Thus, my first iteration was complete, and following the direction of the IMDP, I would repeated this process for the remainder of the forces noted on the IRCPAT until all forces had been implicitly calibrated and incorporated into the model. For this demonstration, I had no other system pairs to calibrate, and thus, no further implicit calibration was necessary. Once all additional forces described in the IRCPAT were implicit calibrated, I used the final implicit calibration data as a reference point, and recorded the baseline values for the ESINQ factors of each agent, as well as the meta-model describing the P_v based on the

FR. This step established a baseline set of conditions from which all future expansions of the model could be measured to account for the impacts of the ESINQ factors of interest, as will be seen in part B2a. This data can be seen in Figure 77.

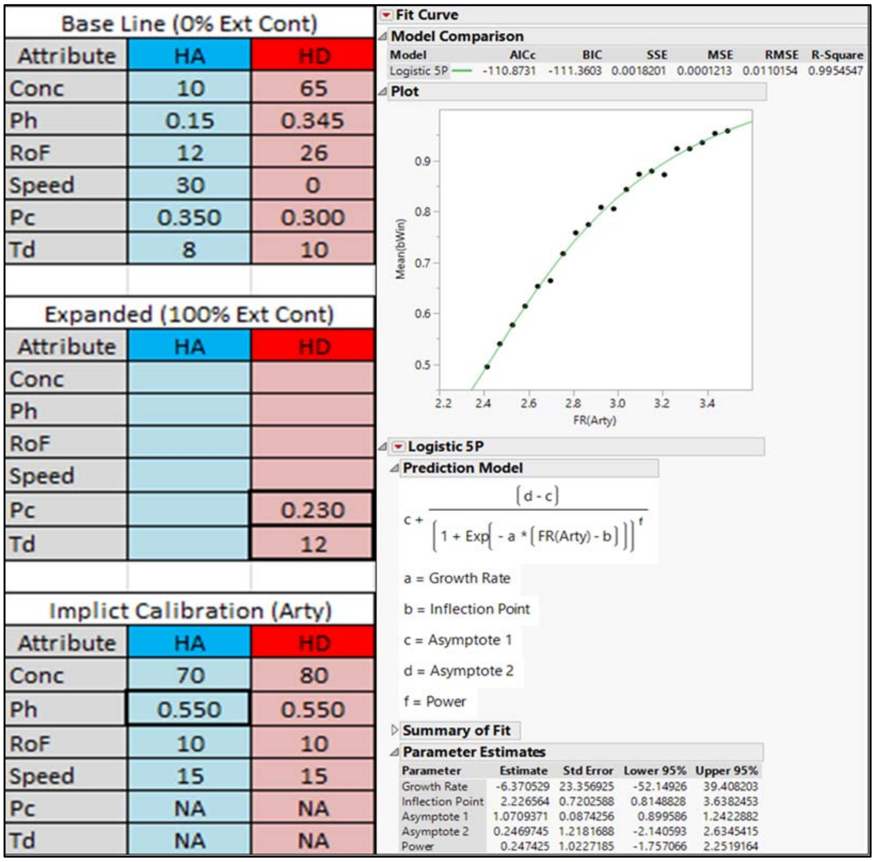


Figure 77. ESINQ Expansion Reference Point

This data served as a reference point for my manipulation of the model to observe the impacts from the ESINQ factors of interest. There was no need to record all possible agent attributes, because from this point forward, the only the ESINQ attributes of interest would be modified, which based on the EEMM, were Red P_c, and Red T_d. After codifying the baseline statistics, I was able to move on to model expansion.

b. Part B2a: Model Expansion

The intent of this step is to expand the model to account for the ESINQ effects of interest identified during part A of the IMDP. While this was a fairly straight forward

process, requiring only minimal modifications, care was taken in how the modifications were made to ensure the process provided more than a subjective assessment. To do so, I started by importing the ESINQ effects of interest from part A1c/EEMM into the ESINQ bounding tool provided by the IMDP. Then, I identified the number of levels I wanted to represent the impacts from degraded ISR on operations. To keep this demonstration simple, I chose to use just five levels, representing the 0%, 25%, 50%, 75%, and 100% levels of severity. Then, using the values curves provided by the IMDP, I articulated to the best extent possible the expected form, or shape of the response curve, using all possible sources of quantifiable data. Typically, the form of the curve is better understood than the quantifiable impacts, which is why we start here. The scaling of these curves will come later during bounding. While the IMDP recommends the use of SMEs and other stakeholders to verify these curves, because I was acting as the SME for this demonstration, this verification process was unnecessary. The completed IMDP bounding tool is shown in Table 52.

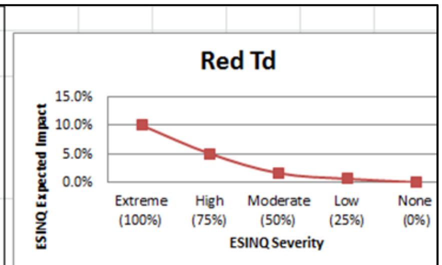
Table 52. IMDP: Part B2a-1 (Initial ESINQ Impact Assessment)

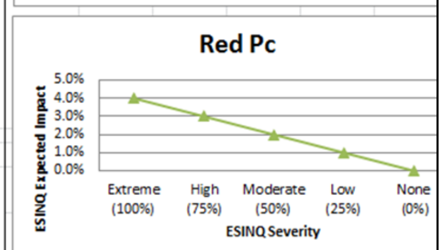
1 Initial ESINQ Response Assessment.

- Import the linked input factors from part A1c/EEMM into column 1 for the 1st ESINQ factor of interest.
- Identify the number of levels of severity you want to represent, more is better, and will yield a better representation of the expected response, but for simple curves, it may not bee needed. This data will drive the creation of response meta-models used for instantiating the DOE. Create a Column for each of these, for this example, I used just 5 levels of severity as seen in Column 2.
- Input expected impact (% change from base value) based on severity for each of the linked input factors into column 2. This should be informed to the largest extent possible by quantifiable sources of impact data. The key is to assess as accurately as possible the expected form, or shape of the response curve. Typically, the form of the curve is better understood than the quantifiable impacts, which is why we start here. The scaling of these curves will come later during bounding. Use the value curves to help support the impact assessment (the curve). This should be assessed by as many SME as possible, leading to an outcome that is acceptable by most.

1	2				
Linked Input Factors	ESINQ Factor Severity (Degraded ISR)				
	Extreme (100%)	High (75%)	Moderate (50%)	Low (25%)	None (0%)
Ave Time/Det	10.0%	5.0%	1.6%	0.6%	0%
Pc	4.0%	3.0%	2.0%	1.0%	0%

o Because this demonstration was looking at the impact of degraded ISR on Blue tanks, in a small protracted fight, the immediate impacts on the force will be relatively small. Thus, the degradation to combat effectiveness is likely small. For other forces, or with other ESINQ factors, these curves could be quite different. it is for this reason that these curves should be done for each agent-ESINQ combination.





As shown in Table 52, I started by attempting to capture the expected impacts that degraded ISR would have on each of the two ESINQ surrogate factors for each of the five levels of severity. I used the curves to help shape the response of each factor based on my understanding of the effect, as well as the expected impacts. For example, for T_d I assessed a maximum impact of 10%. I expected this impact to be small at first, gradually increase with severity, and then increasing polynomial as severity increased above 50%. Using the tool I modified the degradation values of T_d at each level of severity until a curve matching my expectation was achieved. The modification of the P_c surrogate factor was executed similarly.

With the initial ESINQ response assessment complete, I moved on to bounding the response of the ESINQ surrogate factors. Because the user will likely only have a basic understanding to approximate the expected impacts from ESINQ factors, an investigation into the power of the response to impact operational effectiveness is needed to bound the response to a region of feasibility. Using the value curves established previously is extremely subjective, and would likely induce more variability into the model outcomes than would be desired. This step helps refine the estimation of factor settings by bounding them through DOE. To do this, I started by assessing the maximum likely impact from ISR degradation on each of the surrogate factors compared to the contributions from external dependencies, which grounds the assessment of ESINQ impacts to something that has already been accounted for and calibrated in the model. For this example, I assessed this impact to be 20% of the total contribution of external dependencies. Using the response bounding tool, I then calculated the total estimated range of potential degradation across the range of levels of severity, and applied these adjustment factors to the model base values to establish the ESINQ bounding DOE ranges. This step and associated tools can be seen in Table 53.

Table 53. IMDP: Part B2a-2 (Bounding the ESINQ Response)

2 Bounding the Response.

- Because the user will likely only have a basic approximation of the expected impacts from ESINQ factors…which is why they are ESINQ, an investigation into the power of the response to impact operational effectiveness is needed to bound the response to a region of feasibility. Using the values from above is extremely subjective, a best guess, and would likely induce more variability into the model outcomes than would be desired. This step helps refine the estimation of factor settings by bounding them through DOE.
- First select a base ESINQ impact value for each factor. To do this, make an assessment of the likely maximum % impact that the ESINQ effect would have compared to the contributions from External dependencies. This grounds the assessment of ESINQ impacts on something that has already been accounted for and calibrated in the model.
    - o For this example, I assess that the maximum of degraded ISR to be roughly 20% of the impacts from external dependencies seen in part A3d, which was captured in the following factors settings:

0% Contribution		100% Contribution		Delta	
Red Pc	Red Td	Red Pc	Red Td	Red Pc	Red Td
0.300	10	0.230	12	-0.070	2.000

Maximum Impact	0.20

    - o Thus, the maximum expected impact from ESINQ effects is:

Estimated Impact	
Red Pc	Red Td
-0.014	0.400

- Import the baseline ESINQ factor settings from part A3d, to include the modification to account for 100% external dependencies. Import just the ESINQ effects identified in A1c/EEMM, using the values from part A3d. Recall, a degradation to Blue forces in this example is shown through a improvement to Red capabilities.

	Imported		Modified	
	HA	HD	HA	HD
Pc	0.350	0.230		0.244
Td	8	12		11.600

- Build a multifactor DOE across the range of impacts established above, using the FR range from B1a. Round where necessary in the direction of an expanded range. For a better model fit, apply the range to both sides of the base value, failure to do this risks a flawed fit which can induce anomalies into data analysis.

DPs	Factors	Low	Base	High
1	# Blue Tanks	37	42	56
2	Red Td (sec)	11.0	12.0	13.0
3	Red Pc	0.216	0.230	0.244

Following the establishment of the DOE ranges, I used a six factor 2nd order NOLH design to produce the data necessary to bound the ESINQ factors. I stacked the

design six times and replicated it 200 times, for a total simulation run size of 84,000. The analysis of this data focused on establishing a set of surrogate values where the maximum impact to operational effectiveness was close to the estimated maximum impact from the ESINQ effects used to compare external dependencies. In this example that was roughly 20%. Additionally, because we established that external dependencies contributed around 19% of the RCP of the Blue force according to the FA-SWN, I was looking for a maximum impact to RCP from ESINQ effects of roughly 4%, or about a 7% impact to P_v. This provides us the ability to bound the maximum impact from ISR degradation using two metrics, maximum impact to the surrogate factors as well as the maximum impact to P_v based on the contributions from external dependencies. Both of these curves can be seen in Figure 78.

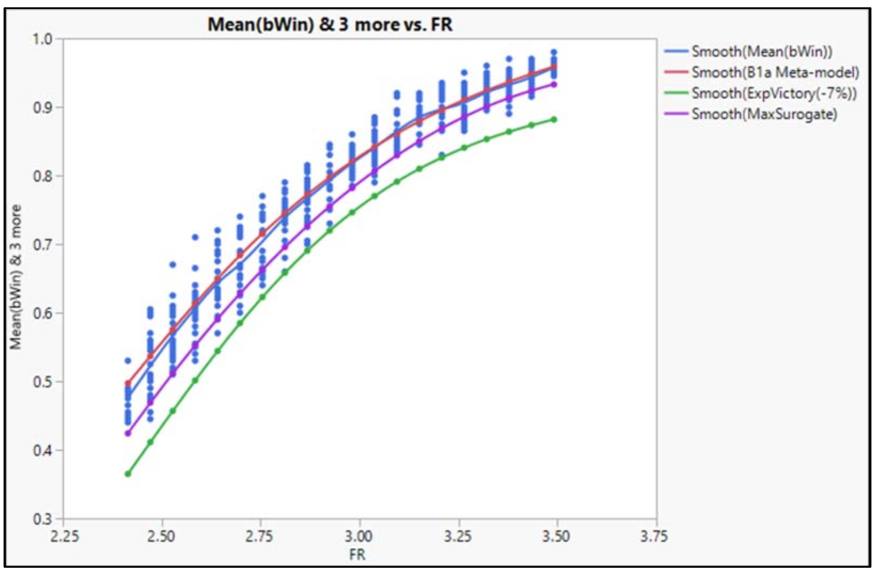


Figure 78. Part B2a-3 (ESINQ Response Bounding)

As shown in Figure 78, each of the 420 DPs from the DOE was distributed about the meta-model curve developed in part B1a, which represents the potential outcomes from the fully calibrated operational model. The green curve was the lower bound, representing the maximum possible degradation based on the impacts to RCP, which was 7%. The purple curve representing the upper bound, which highlighted the maximum impact due to surrogate factor degradation determined through the DOE, which for this

example resulted in roughly a 4.25% degradation. It is the responsibility of the user to fully investigate the difference between these two bounding curves, and based on that analysis; make a decision on which they will use. With this in mind, there are three general options in which the user can take to make this determination. First, the user can choose to use the estimation based on the impacts to RCP (the green curve), which requires the expansion of the DOE ranges and repeated DOE until the results capture that curve. Second, the user can choose to use the DOE results (the purple curve), which estimates the maximum impact based on impact to surrogate factors. Third, the user can chose a hybrid, where the estimation is made based on the relative confidence in both of the bounding estimates, and thus, the resulting curve will fall somewhere in between. This option would also require expanding the DOE ranges to capture the desired curve, and will likely provide a more neutral outcome. For this example, my confident in the assessment of T_d and P_c as primary surrogates and the relative impact to each of these due to ISR degradation was fairly high. Thus, I used this curve to represent the maximum impact rather than the more generalized 20% maximum degradation at the lower bound. I believed that this assessment was more realistic given the scenario for this demonstration, and under scrutiny, it seemed to meet face validation. Following my analysis, the following surrogate factor settings provided the most robust option for representing the desired effects while maintaining consistency with the surrogate meta-model, the contour profiler of which can be seen in Figure 79.

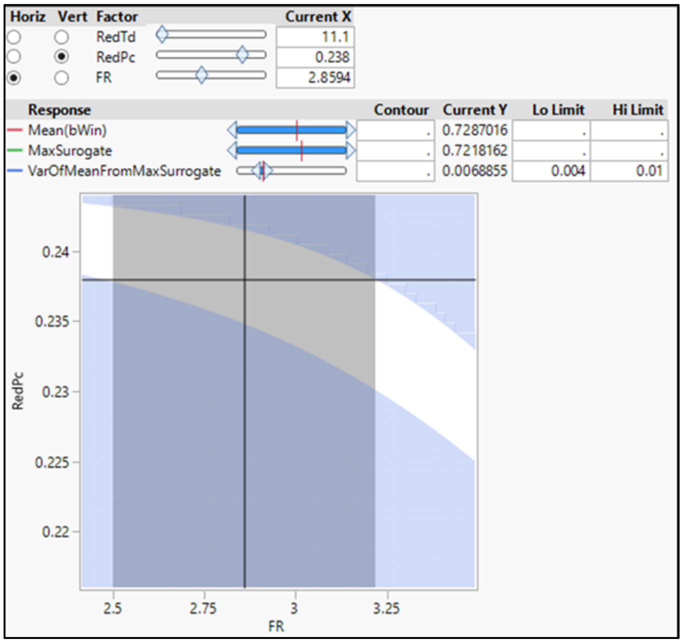
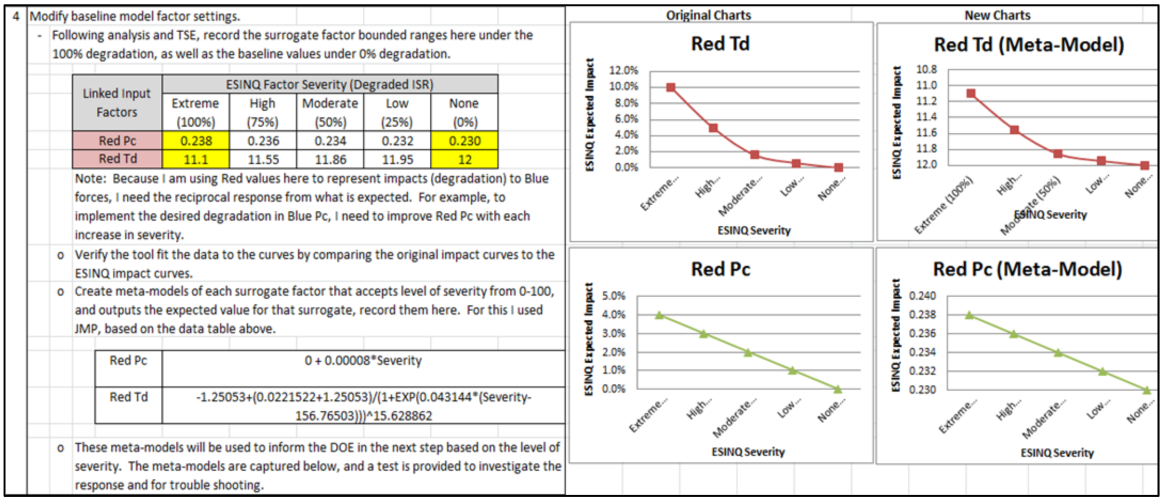


Figure 79. ESINQ Surrogate Bounding Estimates

To make the determination of surrogate factor settings, I started by modifying the most significant factor other than FR, which in this case was Red $T_{d,}$ until the most stable response across the potential FRs is achieved. Then, I systematically reduced the range of the mean from the maximum surrogate value and modified Red P_c until the minimum variance was achieved while ensuring that the entire FR region of interest was still feasible. This resulted in a Red T_d of 11.1 and a Red P_c of 0.238, with a variance from the maximum surrogate curve between 0.4% to 1% P_v. With the bounding of ESINQ responses complete, and a set of ESINQ surrogate factor settings established that would represent the maximum impact from ISR degradation, I moved on to modifying the baseline model factor settings to represent the expected impacts for the remaining levels of severity. I accomplished this by using the supplied tool, starting by establishing the upper bound of degradation by importing the ESINQ surrogate factor settings identified in Figure 79 into the 100% degradation column of the tool. Then, to establish the lower bound, I imported the base line value settings from part B1a into the 0% degradation column. Following these inputs, the expected values for each of the ESINQ surrogate

factors were calculated for each intermediate level of severity. This step and the instantiated tool can be seen in Table 54.

Table 54. IMDP: Part B2a-4 (ESINQ Response Curve Meta-models)


4 Modify baseline model factor settings.

- Following analysis and TSE, record the surrogate factor bounded ranges here under the 100% degradation, as well as the baseline values under 0% degradation.

Linked Input Factors	ESINQ Factor Severity (Degraded ISR)				
	Extreme (100%)	High (75%)	Moderate (50%)	Low (25%)	None (0%)
Red Pc	0.238	0.236	0.234	0.232	0.230
Red Td	11.1	11.55	11.86	11.95	12

Note: Because I am using Red values here to represent impacts (degradation) to Blue forces, I need the reciprocal response from what is expected. For example, to implement the desired degradation in Blue Pc, I need to improve Red Pc with each increase in severity.

- o Verify the tool fit the data to the curves by comparing the original impact curves to the ESINQ impact curves.
- o Create meta-models of each surrogate factor that accepts level of severity from 0-100, and outputs the expected value for that surrogate, record them here. For this I used JMP, based on the data table above.

Red Pc	0 + 0.00008*Severity
Red Td	-1.25053+(0.0221522+1.25053)/(1+EXP(0.043144*(Severity-156.76503)))^15.628862

- o These meta-models will be used to inform the DOE in the next step based on the level of severity. The meta-models are captured below, and a test is provided to investigate the response and for trouble shooting.

Following the development of the meta-model curves, I inspected them for conformity with the original curves, ensuring the generate shape of the response was consistent, which for this example they were. Thus, following this verification, I developed meta-models for each of the surrogate factor responses that would accept the level of severity and output the expected adjustment factor for both red T_d and P_c, which will be used to inform the DOE in the next step. At this point, the model could have been updated for any given combination of severity, and following a verification run, analysis would have highlighted the variation in the P_v due to the impacts from degraded ISR for that specific combination of FR and severity. While this improved model would have been useful in itself, because I was interested in developing meta-models that could represent the impact of degraded ISR across all levels of severity, it was unnecessary; all combos were to be explored during the subsequent DOE.

c. Part B2b: DOE

The intent of this DOE was to produce sufficient data to enable detailed analysis in the next step, where impacts to Blue P_v based on FR and ISR degradation would be quantified, and a meta-model of the response codified. Following the direction of the

IMDP, I started by establishing the bounds for the FR based on the directionality of the expected response of the ESINQ effects. This was important to ensure the DOE retained enough flexibility in FR to maintain a P_v range between 40% and 95%. In this demonstration I was concerned with assessing the impact of degraded ISR on Blue $P_{v,}$ which was expected to degrade Blue RCP. Thus, the upper bound was extended by 50% of the FR range from part B2a while fixing the lower bound, which resulted in a FR range of 37–65. Next, I expand the upper bound of severity by 25% to allow more flexibility in the design to account for degradation uncertainty. The steps for this step, as well as the DOE range tool can be seen in Table 55.

Table 55. IMDP: Part B2b-1 (DOE Range Bounding)

1 Build the DOE design starting with the FR and levels of severity. Because we are unsure of the response, and want to give the user more flexibility, we will use a wider range of FRs as well as severity.

- Special care must be taken when establishing the bounds for the FR based on the impact of the ESINQ effects of interest. We must ensure the DOE has enough flexibility in FR to maintain a Pv range between 40% and 95%. Thus, if the ESINQ effect will improve RCP, the lower bound must be extended while fixing the upper bound. If the ESINQ effect will reduce RCP, as in this example, then the opposite is true, and we fix the lower bound and extend the upper bound. As a general rule:
    - o If extending the lower bound, extend it by 50% of the difference between the bounds used during part B2a. For this example, that was 37-56 tanks, so the lower bound would be decreased by 9, establishing a new lower bounds of 28.
    - o If extending the upper bound (as we are in this example) do the same, just modifying the upper bound by 9, establishing a new upper bounds of 65.
- Expand the upper bounds of severity as much as the user is comfortable with, which will be based on the accuracy of the meta-models developed in the previous step to capture the response of each surrogate factor. For this example, I choose to expand the range by 25%. This allows more flexibility in the tool to account for degradation uncertainty.

DPs	Factors	Low	Expected	High
1	# Blue Tanks	37		65
2	Severity	0		125
3	Red Td (sec)	Calculated for each Dip using meta-models based on severity		
4	Red Pc			

- o At this point the DOE will only have 2 factors, but will be expanded to include the ESINQ surrogates after the design is built, which will be calculated using the meta-models developed during part B2a. Some considerations for the design:
    - Use a larger design then needed, saturation is key with such a wide range of severity.
    - For this example, I used an 7 x factor 2nd Order NOLH, which has 125 DPs, and can be seen to the right.

Following the establishment of the DOE ranges for these two factors, a 2nd order NOLH design was developed. As directed by the IMDP, to ensure adequate saturation of the solution space I used a seven factor design, which resulted in 125 DPs. Then, to further saturate the design I stacked the design seven times, resulting in an 875 DP design. This two factor design was then copied to a clean spreadsheet, where I added two additional columns, one each for Red T_d and $P_{c,}$ which were calculated using the meta-models developed during part B2a based on the values of FR and Severity at each DP. Finally, based on the models input requirements, some further modification to the data was necessary. For MANA, this required me to set #BlueTanks to discrete values, modify T_d to increments of 0.1, and add a scaling factor for both T_d and P_c. A partial snap shot of the final 875 DP four factor design can be seen in Table 56.

Table 56. IMDP: Part B2b (Consolidated DOE)

#BlueTank	Severity	Red Td	Red Pc
56	41.4	119000	2330
63	121.9	108000	2400
55	51.3	118000	2340
47	93.9	112000	2380
38	112	109000	2390
61	86.8	114000	2370
54	71.7	116000	2360
52	40.6	119000	2330
62	17.9	120000	2310
47	115.8	109000	2390
49	71.5	116000	2360
57	102.7	110000	2380
63	17.2	120000	2310
50	78.7	115000	2360
46	82.4	114000	2370
53	67.5	117000	2350
65	12.2	120000	2310
45	81.1	115000	2360
58	55.6	118000	2340
50	85.6	114000	2370
39	37.2	119000	2330
44	75.7	115000	2360
38	68.6	117000	2350
49	26.1	120000	2320

It is important to note that while T_d and P_c served a critical role as surrogate factors for ISR degradation in the model, following the DOE, they were no longer needed. During analysis, the impacts to Blue P_v were linked directly with ISR degradation severity. Following the completion of the design, the design .csv, the model .xml, and the study .xml were uploaded to the NPS advanced computing cluster, and after each DP was replicated 400 times, resulted in a total of 350,000 simulation runs. After the output data was returned and verified, I was able to move on to the next and final step of the IMDP.

d. Part B2c: Quantifying ESINQ Effects (Analysis)

The contribution of this work was to provide the means (the IMDP) to develop an ESINQ enable model, which was technically completed following during part B2a. However, we have yet to quantify the impacts from ESINQ effects in any meaningful way. The intent of this final step was to conduct a final iteration of analysis of the output data from the large scale DOE executed in the previous step to establish a mathematical representation of the impacts from degraded ISR on the model, specifically the impact to Blue P_v. As directed by the IMDP, I started by first importing the data into JMP and conducting data formatting. In this first step I inspected the data for completeness, translated any modified factors back into their original form, add a column for P_v, and added a column for FR based on the equation used in part B1a. Following the import and organization of the data, I collapsed it using a summary table for severity, FR, Red T_d, and Red P_c, while producing the mean of the Blue P_v. Then, I conducted regression analysis on the data to fit the model. For this demonstration, I used a standard least squares regression to conduct effects screening. Specifically, I fit severity and FR using a 2^{nd} degree factorial and a 2^{nd} degree polynomial to construct my model effects, then used mean P_v as my role variable. Following regression, I conducted analysis starting with the fit, as summarized in Figure 80.

RSquare	0.987888
RSquare Adj	0.987817
Root Mean Square Error	0.017648
Mean of Response	0.825656
Observations (or Sum Wgts)	858

Figure 80. IMDP: Part B2c (Summary of Fit)

As shown in Figure 80, the model fit had an adjusted R^2 of 0.988, denoting a very good fit between the data and the resulting meta-model. This was far better than I was expecting for a combat model, which due to their highly stochastic nature, often have extremely wide ranges of variability, which typically reduce the overall fit. To investigate any such variability, analysis of variance was then conducted to gain a better understanding of the model, the results of which can be seen in Figure 81.

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	21.644337	4.32887	13898.69
Error	852	0.265363	0.00031	Prob > F
C. Total	857	21.909700		<.0001*

Figure 81. IMDP: Part B2c (Analysis of Variance)

The analysis shows that the model accounts for nearly 99% of the observed variability, with roughly 1% of the variability attributed to error. The models ability to capture the majority of the variability, coupled with the relatively insignificant mean square of the error component, results in an extremely large F Ratio. Knowing that the variability of combat outcomes can approach 100% as the forces approach parity, I am encouraged with the results, which likely derive from the high number of degrees of freedom during the analysis. The Prob > F value of less than 0.0001 is also encouraging, indicating a high probability that the model is in fact capturing the majority of the variability. Following analysis of variance, I inspected the sorted parameter estimates to look for significance in the response and directionality. It is important to understand what factors are significant, the direction of their response, and the inter-dependence of the

factors to gain better insight into the function of the model. Figure 82 shows the sorted parameter estimates.

Term	Estimate	Std Error	t Ratio	Prob>|t|
FR	0.3234164	0.001299	249.04	<.0001*
(FR-3.20929)*(FR-3.20929)	-0.262041	0.003158	-82.99	<.0001*
Severity	-0.000257	1.651e-5	-15.56	<.0001*
(Severity-62.5446)*(FR-3.20929)	0.0003078	0.000036	8.54	<.0001*
(Severity-62.5446)*(Severity-62.5446)	-2.228e-6	5.086e-7	-4.38	<.0001*

Figure 82. IMDP: Part B2c (Sorted Parameter Estimates)

As shown, FR dominates the response with regard to P_v, which was expected, as well as its 2nd order interaction. Severity of ISR degradation also had a fairly significant impact, though less than FR. Of special interest is the significance of the two-way interaction between FR and severity, which denotes a non-linear interaction between the two and provides some useful insight into the model. Non-linearity in models often highlights potential opportunities or concerns that should be understood before moving forward. To investigate this non-linearity further, I used a contour profiler to perform TSE, which can be seen in Figure 83.

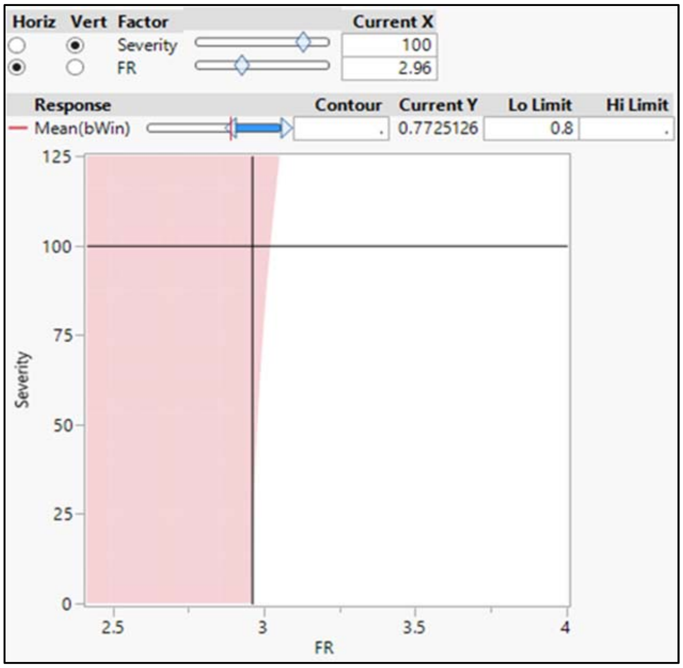


Figure 83. IMDP: Part B2c (Contour Profiler)

To execute TSE I began by manipulating FR and the level of severity to gain insight into the impacts that degraded ISR had on the P_v of the Blue force. What I found is that the impact of severity on P_v is indeed non-linear, having a much greater impact when the FR is lower. Intuitively, this makes sense. Due to the fact that FR dominates the response, and that the impacts of degraded ISR on a relatively short tank battle is likely very small, impacts from ESINQ effects can often lose significance during battles where the Blue force enjoys a large FR. A key observation from the profiler is that while a greater than 80% P_v was possible at a FR of 2.96, once ISR degradation is considered this was no longer the case. At 100% severity of degradation, the profiler suggest that we would need at least a FR of 3.03 to achieve a greater than 80% $P_{v,}$ highlighting a -0.07 (2.36%) degradation in RCP. If the FR was not adjusted to mitigate the impact from ISR degradation, a -2.78% decrease in P_v was incurred, which quantifiably captures the impact from degraded ISR on metrics of operational effectiveness. Thus, the primary end state of this dissertation has been realized. Yet, to provide more utility to the user, who may not be comfortable with or have access to JMP, the prediction expression from the

analysis was used to create a meta-model of the P_v based on the FR and ISR degradation severity, which can be seen in Figure 84.

$$
\begin{aligned}
&-0.1368213406751\\
&+\ -0.0002569378203 * \text{Severity}\\
&+\ 0.32341636103974 * \text{FR}\\
&+\ (\text{Severity} - 62.5446386946387) * ((\text{FR} - 3.20928852593681) * 0.00030782503336)\\
&+\ (\text{Severity} - 62.5446386946387) * ((\text{Severity} - 62.5446386946387) * -0.000002228191)\\
&+\ (\text{FR} - 3.20928852593681) * ((\text{FR} - 3.20928852593681) * -0.2620413962063)
\end{aligned}
$$

Figure 84. IMDP: Part B2c (Meta-Model for Impacts from Degrade ISR)

This meta-model provided me a mathematical representation of the impacts of degraded ISR on the outcomes of the model, specifically the P_v of the Blue force, based on the FR and the level of severity. Using this meta-model, I created a tool that could take the expected level of severity, FR, and FE (part of FR) as inputs and returned the expected impact on Blue P_v and RCP from degraded ISR. This tool can be seen in Table 57.

Table 57. IMDP: Part B2c-2 (Meta-Model Testing Tool)

Force Ratio		2.96		Blue Expected Pv	80.03%
ESINQ Severity		100		Blue Pv (ESINQ)	77.25%
FE		635.76		Blue Impact (Pv)	-2.78%
				Blue Impact (RCP)	-11.44

Using this tool, I tested the meta-model thoroughly to ensure it was functioning correctly and that it provided the expected outcomes based on the analysis conducted in its development. With testing complete, the meta-model could be used to improve other tools – a secondary contribution of this work that will be discussed and demonstrated in Chapter V: Application.

C. SUMMARY

This chapter presented a fully executed IMDP. This demonstration, and its associated products, served to illustrate the overall applicability of the IMDP to quantify the impacts of ESINQ effects of interest on metrics of operational effectiveness. As advances in technology and changing doctrine continue to enforce strategies that pass more of a systems internal tasks to ESINQ sources of combat power, the presence and impact of these effects can no longer be ignored and/or aggregated the models referent; they must be addressed and accounted for separately in the model. By providing a methodology in which users can quantify ESINQ effects and implement them in their models, the IMDP fills known gaps and expands the body of knowledge with regard to M&S and traditional MDPs. The meta-models that are the end state of the IMDP could be used to improve not only the model, but other operational and acquisition support tools as well. These improved tools would then provide a more accurate representation of the system with respect to the OE, and if used in support of decision makers, could improve the quality of their decisions. While the potential use for the meta-models generated through the use of the IMDP is nearly limitless, Chapter V: Application will cover just two such uses, describing the implementation of the meta-models to improve an operational support tool as well as an acquisitions support tool.

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V. APPLICATION

The primary contribution from the execution of the IMDP was the development of meta-models that can describe the impacts of ESINQ effects on metrics of operational effectiveness. These meta-models have a nearly limitless capacity to inform and to improve other tools. In fact, the application of the outcomes of the IMDP to improve current operational and acquisitions decision support tools was a key consideration in the focus of this dissertation. Although the application of the meta-models is outside the scope of the IMDP, the author would be remiss if some of the potential applications of the meta-models were not demonstrated. Thus, the purpose of this chapter is to apply the outcomes from the execution of the IMDP to modern problems. Because of the nearly limitless potential for these meta-models, this chapter will not provide any specifics regarding how to apply the outcomes. Rather, it will provide a description of how the author applied the meta-models to address the gaps identified earlier in this dissertation, specifically by improving of operational and acquisitions decision support tools.

A. OPERATIONAL PLANNING SUPPORT TOOL

Historically, most military plans are developed through detailed assessment of friendly forces, the expected opposing force, and the OE, supported by intelligence, higher guidance, and the experience and knowledge of staff and decision makers. As technology has advanced, so have the tools the military uses to support its operational planning, yet the majority of the force assessment and allocation of forces has remained the responsibility of staffs and leaders. While operational planning support tools play an informative role in this process, they are typically only used for validating other more subjective, human centric decisions and assessment processes. A contributing factor to this inefficiency is the inability of modern tools to provide anything other than the simplest of comparisons between forces, offering only a rough assessment of RCP. The FRC is a perfect example to highlight the inadequacy of current support tools; an instantiated version of which can be seen in Figure 85.

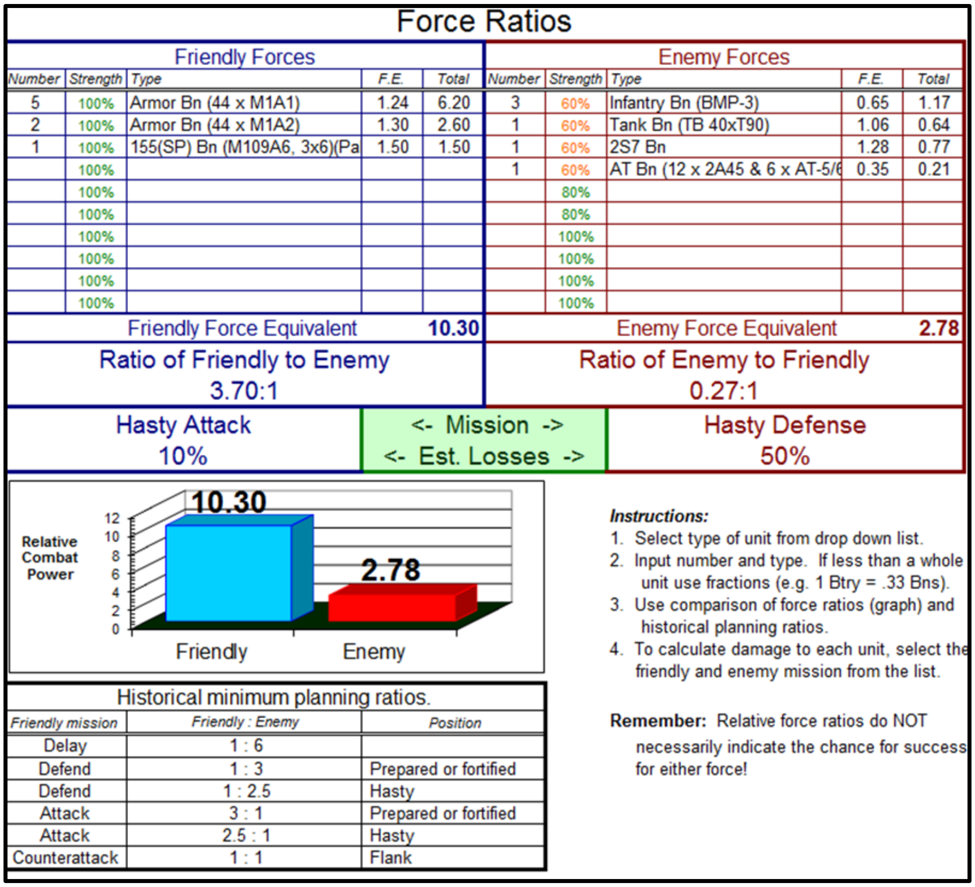


Figure 85. Force Ratio Calculator. Source: Craig (1999).

As the primary tactical planning support tool used by the Army since its development by MAJ J. Craig in 1999, the FRC has a fairly wide distribution and is routinely used during planning for training and combat operations. While the FRC has been impactful in supporting operational planning, specifically with regard to force allocations, it has some significant shortcomings that have critically undermined its usability and effectiveness in supporting decision making. Of these shortcomings, there are five that should be addressed. First and foremost, the FRC is a simplified tool that aggregates combat into fairly simple quantifiable system versus system metrics, without accounting for additional sources of combat power like ESINQ effects. Second, as an aggregation tool, the FRC cannot account for the synergist impacts of modern combined arms operations on today's battlefield. Third, because of its low resolution, the FRC is not able to accurately account for forces sizes below the BN level, which is no longer

realistic in the modern era of combat. Fourth, the FRC has had few updates over the past 18 years, leaving the tool dated and unable to address many modern systems. These same issues are seen in the source data as well; the FA-SWN and the COFM are in dire need of updates or replacement. Finally, the FRC fails to maximize its utility for the user, missing opportunities to better support decision makers by making the tool more useful. To address some of these issues, the FRC was updated to create the IRCPAT, as seen in Figure 86, giving the tool more utility to modern day users.

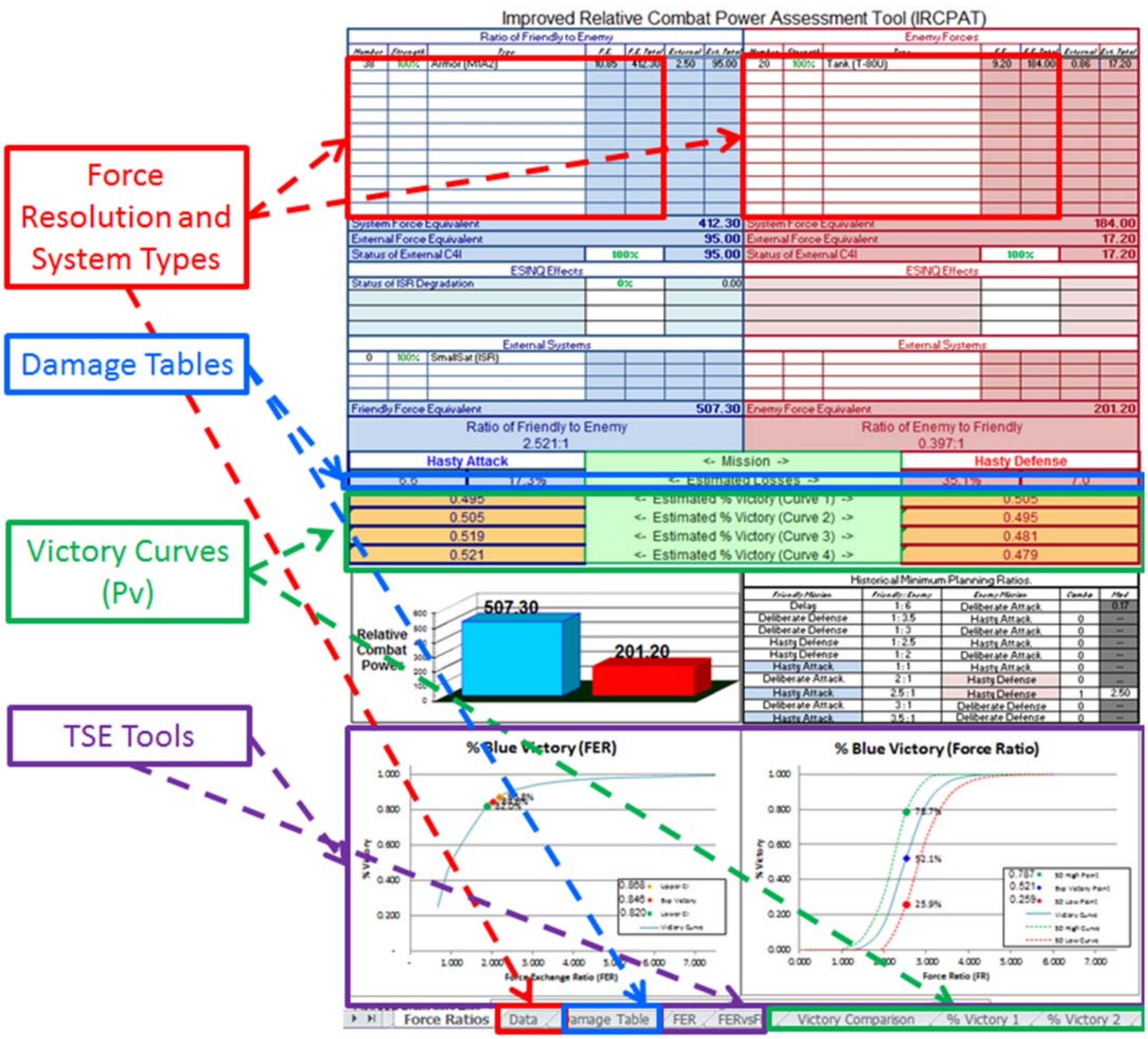


Figure 86. IRCPAT

As shown in Figure 86, the User Interface (UI) was significantly modified to provide the user with better manipulation of the tool as well as a more detailed assessment of RCP. This modification had four primary steps. First, the data tab was updated to provide finer resolution of the force sizes and to add new system types like the Stryker that were absent in the FRC. Next, the damage table was replaced using a meta-model, which accepted the FR and the mission set from the user to calculate the expected losses for each force. Because the FRC determined expected losses through a look-up table, it could only provide seven discrete values. By developing a continuous meta-model of this discrete response, the IRCPAT solved a significant issue with the FRC and can now more accurately assess expected damage across the entire range of potential FRs. Next, four victory curves were integrated into the IRCPAT to provide the user more functionality. These curves were loosely based on the works of (Helmbold 1969) and (National Research Council Committee on National Statistics 2003), which sought to establish historical linkages between FR and P_v. By providing a range of victory curves for the user to choose from, a more flexible estimation of the P_v can be achieved. This flexibility allows the user to modify the tool as needed based on their confidence in the assessment and the level of risk they are willing to accept. Finally, a set of TSE tools were added to the IRCPAT to support a better representation of the RCP trade space. These tools provide the user the ability to visualize the impacts that modification to the FR and the expected FER can have on the P_v. With the IRCPAT created, it was now possible to further improve the tool by applying the outcomes of the IMDP from the previous chapters.

1. Application of the IMDP Outcomes

The first improvement offered by the IRCPAT was the delineation between internal and external sources of system combat power. During part A2b and A3d, the IMDP quantified the contribution from external sources of internal combat power, which can be degraded separately based on the status of those external systems. Thus, the IRCPAT was then updated to account for these contributions to RCP individually, as seen in Figure 87.

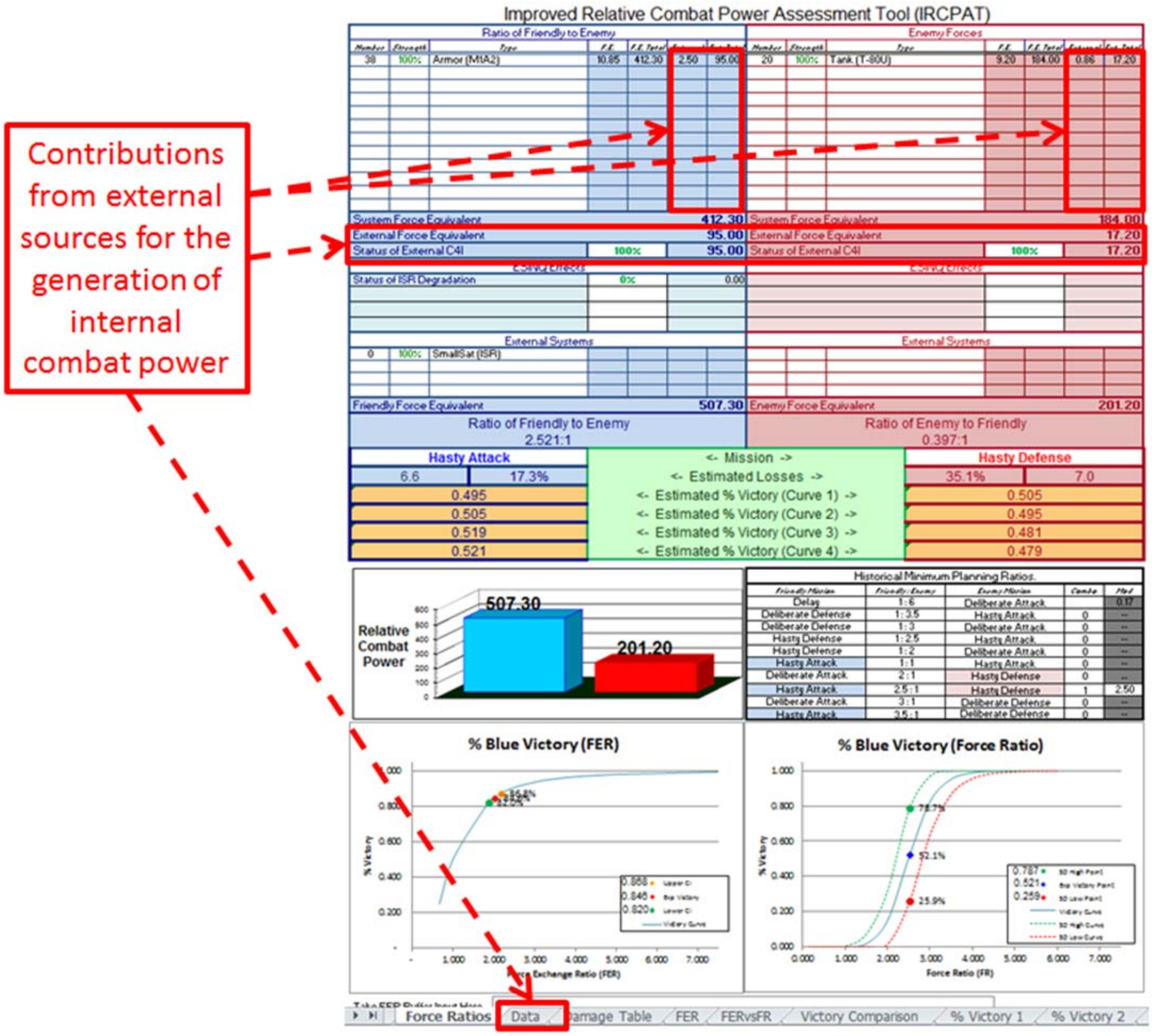


Figure 87. Expanded IRCPAT (External Dependencies)

As shown in Figure 87, the IRCPAT was updated to provide a more accurate assessment of system combat power by delineating between the two sources of internal combat power: power that is inherent in the system and power that is dependent on external resources. While the total potential FE of each system remains the same, it is now possible to degrade the external sources independently; the impact of which is dependent on the dependency of each system on those external sources. The dependency is greater for higher tier systems, and thus, the impact to the system FE is greater than a lower tier system. By accounting for this third area of combat power contributions, the IRCPAT can provide a much more realistic understanding of opposing systems.

The second improvement offered by the IRCPAT was the inclusion of ESINQ effects as additional contributors to the generation of RCP. During part B2c, the IMDP quantified the impacts of ESINQ effects of interest on metrics of operational effectiveness through the generation of meta-models. For this work, the ESINQ effect used for demonstration was degraded ISR: the meta-model for which accepted FR and level of severity and then provided the expected impact to RCP of the Blue force. Because the IRCPAT provides all the necessary inputs, the meta-models can be applied, which is why we (other than partial validation) maintain calibration with a reference tool. Figure 88 shows the IRCPAT following the modification for ESINQ effects.

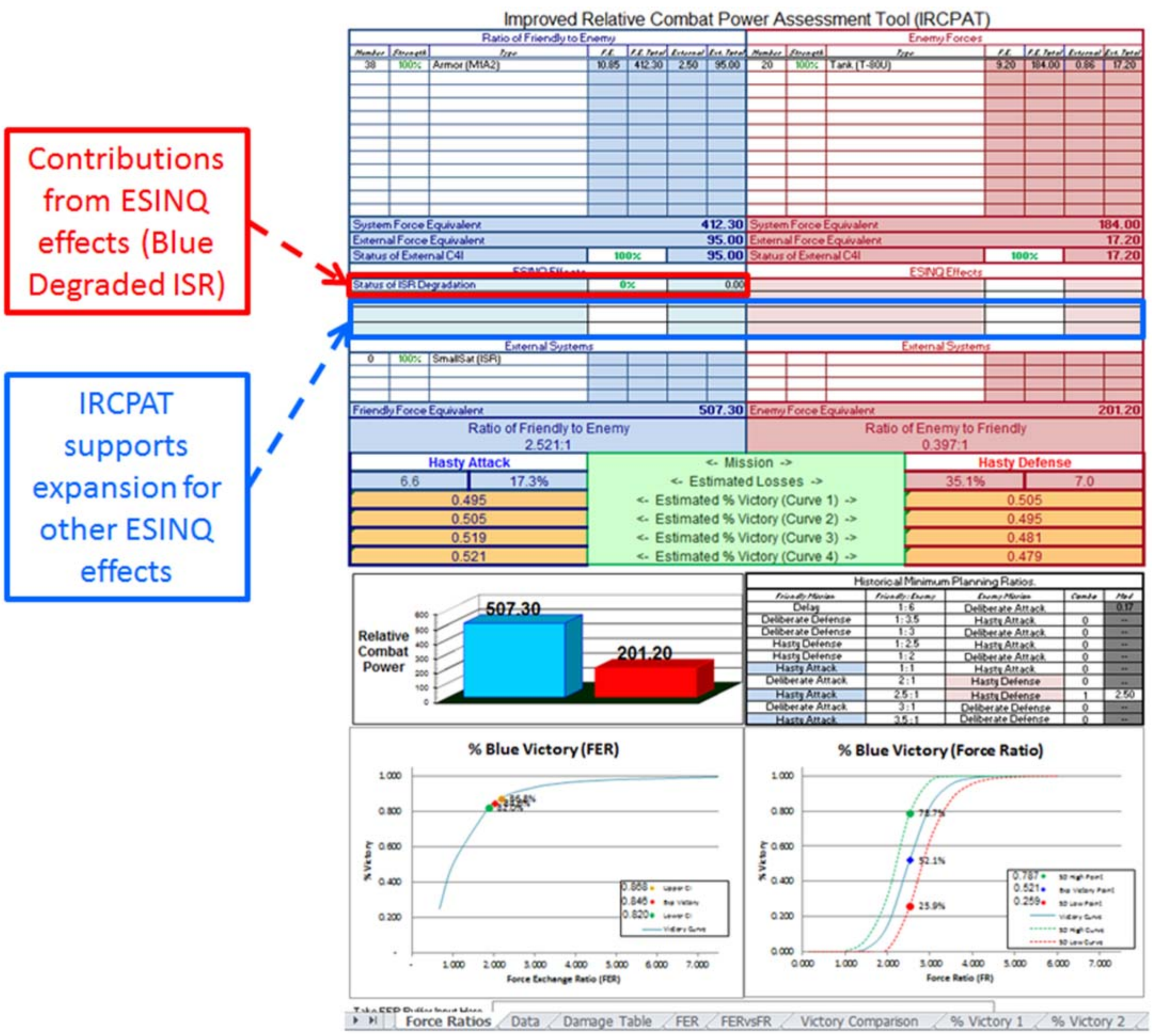


Figure 88. Expanded IRCPAT (ESINQ Effects)

As shown in Figure 88, the IRCPAT was updated to account for the impacts from degraded ISR on the Blue force by including the meta-model generated at the completion of the IMDP. As before, the total potential FE of each system remains unchanged, but it is now possible to degrade the portion of Blue RCP based on the level of degradation severity. As the user assesses higher levels of severity, based on the levels (0% to 100%) used during part B2a of the IMDP, the degradation of Blue RCP increases. Additionally, because of the flexibility of the IRCPAT, other ESINQ effects can be included following the development of their meta-models. After this final improvement, the IRCPAT can now address all four of the potential contributors of combat power, proving a much more complete understanding of the actual OE. With the improved IRCPAT complete, a demonstration of its utility is appropriate.

2. Demonstration

To demonstrate the utility of the IRCPAT, it was instantiated for the example scenario used in Chapter IV. To do so, some user inputs were required, including status of external C4I, and ISR degradation. For this demonstration, external C4I was set at 95% to denote the general status of external support sources, while the ISR degradation was set at 50%, denoting a decrease in access to space based ISR assets. The instantiated IRCPAT for this scenario can be seen in Figure 89.

Improved Relative Combat Power Assessment Tool (IRCPAT)

Ratio of Friendly to Enemy							Enemy Forces						
Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total	Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total
42	100%	Armor (M1A2)	10.85	455.70	2.50	105.00	20	100%	Tank (T-80U)	9.20	184.00	0.86	17.20
6	100%	M270-A (MLRS)	10.16	60.96	2.35	14.10	6	100%	Arty-220mm (9P140))	5.25	31.50	0.49	2.94

Friendly			Enemy		
System Force Equivalent		516.66	System Force Equivalent		215.50
External Force Equivalent		119.10	External Force Equivalent		20.14
Status of External C4I	95%	113.15	Status of External C4I	100%	20.14
ESINQ Effects			ESINQ Effects		
Status of ISR Degradation	50%	-4.32			
External Systems			External Systems		
Friendly Force Equivalent		625.49	Enemy Force Equivalent		235.64
Ratio of Friendly to Enemy 2.654:1			Ratio of Enemy to Friendly 0.377:1		

Hasty Attack		<- Mission ->	Hasty Defense	
8.1	16.8%	<- Estimated Losses ->	36.5%	9.5
0.515		<- Estimated % Victory (Curve 1) ->	0.485	
0.552		<- Estimated % Victory (Curve 2) ->	0.448	
0.587		<- Estimated % Victory (Curve 3) ->	0.413	
0.624		<- Estimated % Victory (Curve 4) ->	0.376	

Figure 89. IRCPAT (Application Demonstration)

The IRCPAT has been updated to include the degraded ISR meta-model developed during Chapter IV, specifically formatted to provide a degradation factor with respect to RCP. As shown in Figure 89, the overall RCP of the Blue force has been reduced. When status of external C4I was set to 100% and ISR degradation set at 0%, the Blue RCP was 2.698:1 with a Blue P_v of 65.5%. Following the modification of the external dependencies from 100% to 95%, the RCP dropped to 2.673:1 with a Blue P_v of 63.7%, a 1.8% decrease in $P_{v.}$ After accounting for the 50% degradation in ISR support, the RCP dropped again to 2.654:1 with a Blue P_v of 62.4%, resulting in an additional 1.3% decrease in Blue P_v. Thus, the IRCPAT has highlighted the operational impacts from degradation of both external dependencies as well as ISR, which induced a 3.1% decrease in Blue $P_{v.}$ What is unique about the IRCPAT is that neither external dependencies nor ESINQ contributors to combat power were previously accounted for in the FRC or in any other operational decision support tools. Thus, the IRCPAT provides

users an improved operational decision support tool, supporting TSE by exploring the potential impacts of the OE and decisions on Blue P_v.

3. Discussion

As highlighted in Chapter II, there are some significant gaps in current Army operational planning support tools, specifically in their inability to accurately account for contributions to RCP from non-traditional sources of combat power. This inability to accurately represent the OE has limited the capabilities of most tools. Fortunately, because the IMDP provides a method for quantifying the impacts to operational effectiveness from external dependencies and ESINQ effects, the outcomes of the IMPD can be used to improve operational decision support tools like the IRCPAT. While improving the FRC to address these gaps was not directly related to the intended contribution of this dissertation, it represents an important secondary contribution.

The IRCPAT fills observed gaps by accounting for the contributions of external dependencies and ESINQ effects on the generation of combat power, providing users with a more detailed and complete analysis of the RCP of opposing forces. Additionally, the IRCPAT provides more in-depth analysis of RCP, to include assessments of P_v based on mission set, and TSE, where the modifications of FRs and expected FERs can be assessed for their impacts to Blue P_v. While the application described here was just a simple demonstration, and really only good for the specific mission set and scenario, with further development and execution of the IMDP to assess other mission sets, scenarios, and ESINQ effects, like SATCOM and PNT degradation, the IRCPAT can be improved even further. By improving its accuracy, usability, and relevance, the IRCPAT will be far more useful to current Army operational planning. These improvements will have immediate operational relevance to planners Army wide, and should significantly reduce the underestimation of combat power so routinely seen in the FRC.

B. ACQUISITION TRADE SPACE EXPLORATION TOOL

Similar to modeling in support of operational planning, U.S. military acquisitions also depends on M&S to support decision making. In fact, practitioners of MBSE place special emphasis on the importance of integrating M&S into the SE process. For the most

part, these acquisitions support tools are software packages that engineers use to support systems engineering during design, development, and tradeoff analysis. Software packages like CORE and Innoslate provide users a host of tools to characterize the system through the development of key SE architecture documents. Yet these documents are not enough, and to implement the products in a more synchronized manner, most engineers employ an overarching design process to provide a more complete process for employing M&S. By formalizing the process for integrating architecture development products into external models, Beery was able to define a more accurate representation of the system's interactions with the OE. Thus, the overall understanding of the system and its interactions are improved, yielding more insightful TSE. It is because of this improved capacity and the robustness of these models to explore the system trade-space through OEM, that the MBSE MEASA will be used for the development of the acquisitions support tool. The steps of Beery's MBSE analysis methodology can be seen in Figure 90.

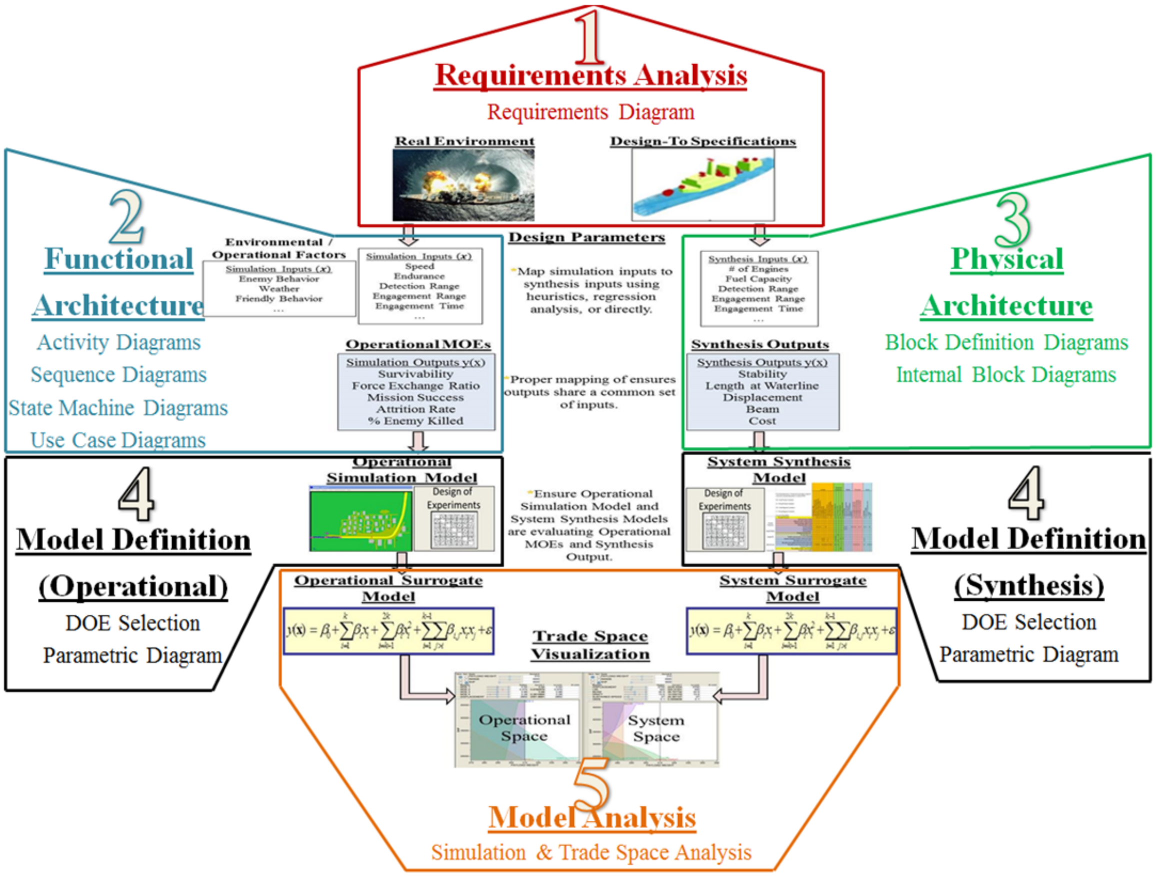


Figure 90. MBSE Analysis Methodology. Source: Beery (2016, 86).

The MBSE MEASA can be broken down into three phases: the systems architecture phase, which includes requirements analysis, functional architecture, and physical architecture; the modeling phase, which includes both operational and synthesis model definition; and the analysis phase. The execution of the MBSE MEASA results in linked operational and synthesis models, enabling the synchronized TSE of the system. When implemented in the OE captured by the operational model, the linked models provide a powerful tool for assessing the impacts of system design trade-offs on operational effectiveness. Unfortunately, even armed with improved analysis methodologies like Beery's MBSE MEASA, the Army space acquisitions community has continued to have a fairly poor success rate with regard to its space R&D programs. This failure rate can often be attributed to a lack of analysis during the early phases of the acquisitions process, which is what MBSE analysis methodologies were intended to

avoid. Thus, a discrepancy was identified, highlighting some shortcomings of MBSE analysis methodologies that limited both their usability and effectiveness.

The author believes the primary reason for this discrepancy is that most MBSE analysis methodologies use traditional MDPs to develop their models, which do not account for ESINQ effects. Thus, during space acquisition, which deals primarily with ESINQ effects, the underlying models are far more inaccurate than those used during the modeling of traditional (non-ESINQ) systems. These inaccurate models inform the decision making process and result in flawed outcomes, supporting the high failure rate observed in space acquisitions. The use of traditional MDPs also explains why the discrepancy has not been identified earlier, because traditional SE processes work exclusively with quantifiable data, and thus, have not generally needed to account for ESINQ factors. While a great improvement to previous work, Beery's MBSE MEASA uses traditional MDPs, which only address explicit physical system design parameters. Thus, the operational and synthesis models that are so foundational to Beery's work are inaccurate because they cannot account for all potential sources of combat power, specifically external dependencies and ESINQ effects.

1. Application of the IMDP Outcomes

When applied to Beery's MBSE MEASA, the IMDP improves the underlying MDP, allowing the methodology to generate a more complete operational model, one which can account for external dependencies and ESINQ effects. The application of the IMDP to the MBSE MEASA can be seen in Figure 91.

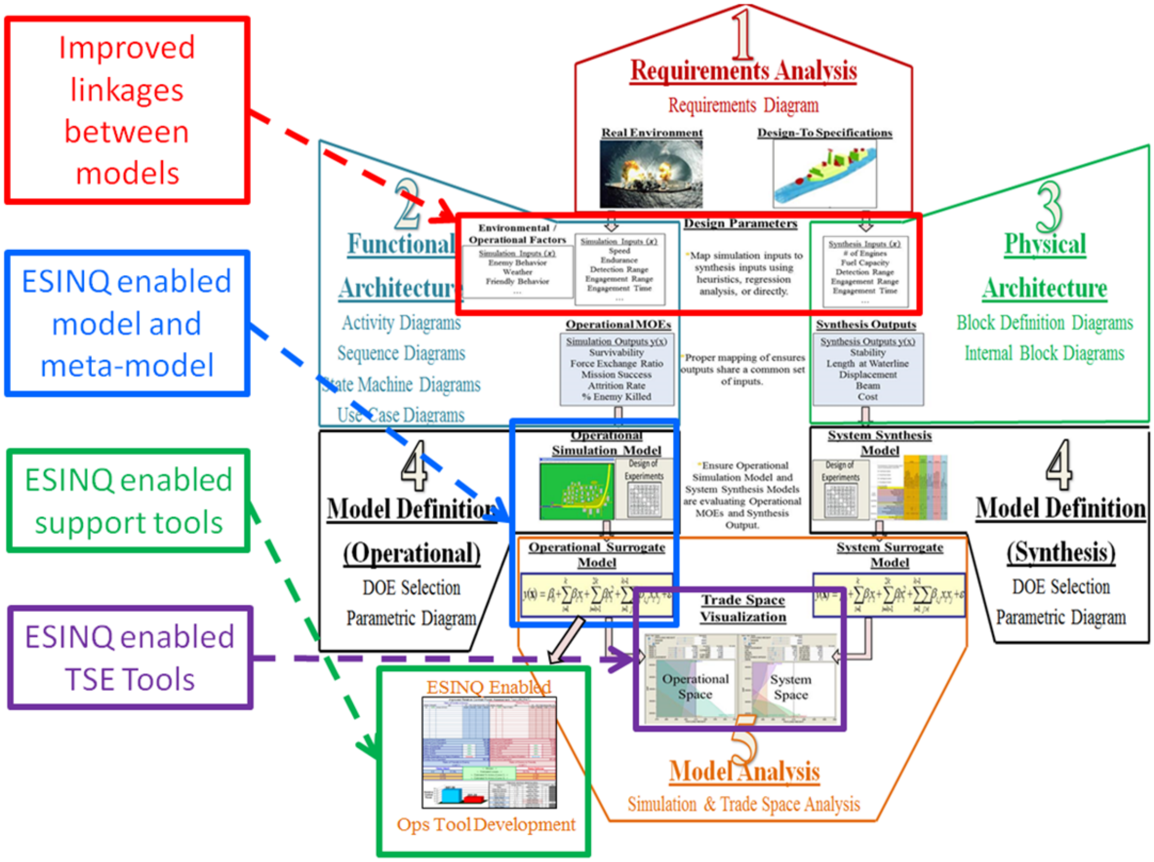


Figure 91. IMDP Applied to the MBSE MEASA.
Adapted from Beery (2016, 86).

By applying the IMDP to the MBSE MEASA we achieve four primary outcomes. First, the IMDP supports more robust linkages between the design parameters of the operational and synthesis models. Previously, the MBSE MEASA used only quantifiable factors for these linkages, but by expanding these potential factors through the use of the IMDP, the linked models are now capable of accounting for ESINQ factors during TSE. Second, the operational model is developed using the IMDP, which provides a much more accurate model than the traditional MDP used by the MBSE MEASA. This improved understanding sets the conditions for the development of ESINQ-enabled meta-models. Third, the operational support tools can be expanded to include the external system of interest. While this step is similar to the MBSE MEASA, the significant difference is that both the tool and the system are now ESINQ-enabled, providing a more accurate representation of the system than possible using just the MBSE MEASA.

Finally, the ESINQ-enabled operational model is linked with the synthesis model using the MBSE MEASA. Following analysis of the data from the linked models, TSE can be conducted to explore the impacts that design changes to the system can have on operational effectiveness. While this step is identical to Beery's, the TSE conducted here can include considerations for ESINQ factors, allowing users to address all four of the potential contributors of combat power as discussed in Chapter II. This improved understanding will proving a more complete exploration of the solution space during early phases of system design, and in turn, provide more accurate information that should support better decisions regarding the allocation of resources during space acquisitions.

2. Demonstration

To demonstrate the utility of applying the IMDP to the MBSE MEASA, a fairly significant amount of work was necessary to set the conditions for producing an ESINQ-enabled TSE tool. To avoid an overly complex and detailed demonstration of this application, this work will forgo as much of the detail of the MBSE MEASA as possible, directing the reader to Beery's work (2016). Likewise, rather than developing an entire synthesis model to support this demonstration, this work used the synthesis model developed by Mike Ordonez during his thesis work titled "Developing and Applying Synthesis Models of Emerging Space Systems" (Ordonez 2016). In his work, Ordonez executed a systems engineering process similar to that of Beery's MBSE MEASA. Thus, by using the previous work of both Beery and Ordonez, the development of the required SE products and synthesis model can be avoided, and instead allow us to focus this demonstration on the application of the IMDP and its outcomes to improve acquisitions support tools. To set the conditions for this demonstration, the following mock acquisitions scenario and narrative was developed to drive the MBSE MEASA.

a. Acquisitions Scenario: SmallSats

Driven by directives from the DOD, the Army has expressed interest in acquiring cross-domain solutions of ISR disaggregation and redundancy. This interest is codified in numerous sources of doctrine, and requires U.S. forces to "change our mindset from simply increasing the density of ISR capabilities to evaluating our methodologies for

employing and integrating ISR assets" (DOD 2011b, 19). To address this requirement, the Army is interested in SmallSats and the utility they can bring to the ground fight. Unfortunately, the Army has little familiarity with space systems and has expressed concerns regarding their potential costs compared to their expected contributions. To mitigate these concerns, the Army has asked that early system analysis be conducted to estimate the expected impacts that SmallSats can have on operational effectiveness. Additionally, the Army has asked how many of these systems would be needed to mitigate the impact from a moderate level of ISR degradation, and what the potential cost of this solution would be. The Army has stated that while it would like these systems to be as capable as possible, it is willing to trade off goal requirements for increased access, its primary objective for this system, and improved resolution, its secondary objective. Additionally, while cost was not identified as an objective, the Army stated that it would be considered during analysis. The baseline Army requirements and MOEs for the initial analysis were provided, and are described in Table 58.

Table 58. SmallSat Initial Requirements and MOEs

Factor	Unit	Threshold	Goal	Improve
Aperature Diameter	cm	5	100	MIB
Altitude	km	800	300	LIB
Cone Half-Angle	deg	60	10	N/A
Mass	kg	200	50	LIB
# of Satellites	#	6	1	N/A
MOEs				
Factor	**Unit**	**Threshold**	**Goal**	**Improve**
Resolution (GSR)	cm	300	50	LIB
Total Cost	$ (Million)	40	10	LIB
Access	min/day	30	60	MIB

These initial requirements will be used to drive the analysis of the linked models and will serve as the basis for the TSE conducted at the conclusion of this demonstration. To simplify this demonstration the following assumptions were made: threshold values will be treated as hard lines; the Army is not concerned with propellant; the inclination of the SmallSats will be fixed at 60°; and the maximum number of satellites should be capped at six. With an improved understanding of the scenario, the requirements, and the assumptions, we can now begin the demonstration.

b. The MBSE MEASA Step 1–3: Systems Architecture

To highlight the potential utility of applying the IMDP to support better TSE, modifications to the MBSE MEASA were required to support the ESINQ-enabled operational and synthesis model linkages necessary for an improved TSE. For the MBSE MEASA, these modifications were fairly straight forward, with the only significant variation from Beery (2016) coming from two primary sources, each of which will be discussed in greater detail. First was synthesis factor translation and mapping, which captured the expected impacts of the system as well as the factors that will represent those impacts in the operational model. Second was the establishment of input factor linkages, which established common inputs between the ESINQ-enabled operational model and the synthesis model. Additionally, while the IMDP and the EEMM can be used to better inform the selection of the synthesis modeling package, for brevity it will not be discussed here.

(1) Synthesis Translation and Mapping (TSE1)

The intent of this sub-step of the IMDP is to build an understanding of the system and link this understanding to a set of tangible effects that can be used to represent the system's functions within the operational model. The IMDP leads the user to a better model definition of the system's functions through a process similar to parts A1a-c of the IMDP. The only difference here is that we are focused on synthesis factors that are primarily informed by the SysML documents developed during the execution of the MBSE MEASA. This step focuses on the development of the synthesis half of the EEMM, which will be used to link operational and synthesis models, and has two primary purposes. The first purpose is to codify the users' needs of the synthesis model by developing an operation concept. While the Use Case Diagram serves the same function for the system, at no time are such requirements codified for the synthesis model, and thus, an operational concept is useful. The second purpose is to translate the system functions described in the SysML products to tangible factors that will be used to represent those system functions within the operational model. The EEMM supports the mapping of synthesis input factors by providing traceability from system level functions to synthesis input factors; an instantiation of which can be seen in Table 59.

Table 59. EEMM (Synthesis Translation and Mapping)

Synthesis Input						Function Range (SysML documents)				
Maps	Potential Factors	Mapping	Tangable Impacts	Linking	Expected Impacts	Threshold	Goal		Expected Functions (SoS Impacts)	Mitigating System
1	Agent Speed		Increased Pc and Ph of some munitions	←	Increased SA/tgt Pc and Ph	300	50	LIB	GSR: Provide High resolution Imagery (cm)	ISR SmallSat
1	Ph / Discharge		Better SA, faster decision making and Pace of battle	←	Increased collection capacity	30	60	MIB	Access: Maximize Mean time per day (min)	
2	Pc									
2	Ave Time/Det									
1	Rate of Fire									

The EEMM starts by capturing the expected functions of the system, as characterized in the supporting SysML documentation. The system functions are then expanded and translated in terms of expected impacts, which are then linked to tangible impacts on the operational model. Finally, these effects are mapped to factors within the operational model that can best represent them. Although a simplified demonstration, it highlights the ability of the EEMM to maintaining traceability to the originating requirements by facilitating the user's translation of high-level systems engineering functions to the operational model. With mapping complete, we can now establish model linkages.

(2) Establishing Linkages (TSE2)

To use meta-models to link the operational and synthesis models in support of TSE, the two models must share a common set of input factors. Recall that once calibration is complete, mission, agent, and external dependency factors remain fixed for the specific mission set, and only ESINQ factors will be manipulated in the DOE to account for the impacts from ESINQ effects. Thus, prior to the development of the synthesis model, we must ensure that these ESINQ input factors are common within both models. While this step is not unique, having been discussed in most works regarding TSE, what is original to the IMDP is the inclusion of ESINQ factors and the method by which these linkages are established. To link the models, the EEMM is used to map the ESINQ input factors from the operational model to the input factors of the synthesis model. The EEMM, executed for this demonstration, is shown in Table 60.

Table 60. EEMM (Operational and Synthesis Model Linkage)

ESINQ Inputs			Linked Input Factors			Synthesis Inputs	
Ave Time/Det	3	→	Ave Time/Det	5	←	Pc	2
Pc	2	→	Pc	4	←	Ave Time/Det	2
Agent Speed	2	→	~~Agent Speed~~	~~3~~	←	Agent Speed	1
~~Ph / Discharge~~	~~1~~	→	~~Ph / Discharge~~	~~2~~	←	~~Ph / Discharge~~	~~1~~
~~Rate of Fire~~	~~1~~	→	~~Rate of Fire~~	~~2~~	←	~~Rate of Fire~~	~~1~~

Using the synthesis versus operational factor Mapping Matrix from the EEEM, the input factors from both models were linked. The results here show a typical outcome, with roughly 75% of the weighted factors being used following crosslinking. As shown in Table 60, RoF and P_h were both identified as operational and synthesis input surrogates. However, these factors were ignored during screening due to the low number of maps, just one each, and the fact that both factors could be accounted for in other factors, like P_c and T_d. Additionally, while speed was included in the operational model inputs, it was ignored in the synthesis model and thus screened out. Thus, just two factors, T_d, and P_c, will be used to link the models, and their output will generate the meta-models needed to observe the operational impacts from system design changes.

c. MBSE MEASA Step 4: Model Definition

Following the completion of SE Architecture, the first three steps of the MBSE MEASA, we can move on to Step 4, Model Definition. Here both the operational and synthesis models are developed to meet the requirements as outlined in their respective OCs, using the linked input factors identified through the execution of the EEMM. Because the operational model was already developed, it will not be addressed here, and only the synthesis model development will be discussed.

(1) Synthesis Model Development (TSE3)

For this demonstration, the synthesis model developed by Mike Ordonez in his 2016 thesis work was selected. This synthesis model was designed to analyze “the relationship between small satellite design inputs and outputs to provide trade space insights that can assist DOD space acquisition professionals in making better decisions in the conceptual design phase” (Ordonez 2016, v). The work of Ordonez closely parallels

the research interests of this work, and because of the commonality between his model and the operational model, no modification was needed. While the model developed by Ordonez was a relatively simple calculation based model, its potential applications were significant. His model consisted of four input/calculation tabs, two look-up tables, two experimental design tabs, and a trade space analysis tab, which can be seen in Figure 92.

Trade Space Analysis

Please submit input values for each of the blue cells below. The outputs will be calculated and presented in the green cells.

Inputs		Units
GSR	250	cm
Altitude	200	km
Spacecraft Mass	10	kg
Propellant	1	0="No", 1="Yes"
Inclination	50	deg
# of Satellites	4	
Cone Half-Angle	20	deg

Outputs		Units
Total Cost	$ 64,735,118.21	USD
Aperature Diameter	0.87	m
Linear Dimension	0.815	m
Number of Accesses (in 30 days)	4.617	
Mean Access Duration	17.755	secs
Payload Mass	1.73	kg
Spacecraft Weighted Mass	10	kg

Figure 92. Trade Space Analysis Worksheet. Source: Ordonez (2016, 79).

The trade space analysis worksheet shown here takes seven inputs from the user, across a range of potential values from the threshold value to the goal value based on the needs of the user. The tool then provides seven outputs, which are based on meta-models developed following the DOE and analysis of the model. For this demonstration, these outputs included key estimations for resolution, cost, and access, thus providing all three of the primary objectives of the Army. With the models developed, a few other modifications were needed prior to conducting analysis and TSE.

(2) Model Expansion for Synthesis Systems (TSE3a-3c)

Although not required for TSE, we can capture the impact of the system in the reference tool now by expanding the operational model to include the system of interest. Because the application of the resulting synthesis meta-model to the IRCPAT is worth a

brief discussion, a short excursion from the TSE application of interest in this section is appropriate. The primary objective of this step is to better inform the IRCPAT by including synthesis systems of interest, similar to parts B2a-c of the IMDP. To do this, the IMDP helps the user better assess and visualize the expected impacts from the system of interest by bounding the system's impacts through a value based process that is informed by both the stakeholders and the SysML products produced during execution of the MBSE MEASA. For this demonstration, simulated stakeholder interactions were used to develop the value curves, which were based on the authors own experience and expertise. The synthesis impact assessment can be seen in Table 61.

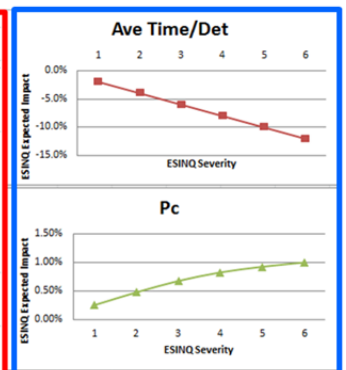
Table 61. IMDP: TSE3a (Synthesis Impact Assessment)

User Synthesis Impact Assessment

1 Initial Synthesis Impact Assessment.

- Import the linked input factors from part A1c/EEMM into column 1 for the 1st ESINQ factor of interest.
- Identify the number of systems you want to represent, more is better, and will yield a better exploration of the internal solution space, and drive more accurate meta-model development, but with the expense of resources. Create a Column for each of these. For this example, I consider up to 6 SmallSats, as seen in column 2.
- Input assessed impact (% change from base value) based on the number of systems for each of the linked input factors into column 2. This should be informed to the largest extent possible by quantifiable sources of impact data, bounded by the impacts and contributions established during part B2a. The key is to assess as accurately as possible the expected maximum (Extreme) impact of the system on each linked input factor. Use the value curves to help support the impact assessment (the curve). This should be assessed by as many SME as possible, leading to an outcome that is acceptable by most. This will represent the improvement to blue RCP per system, things to consider include:
    - o Start by considering the capability of the system to support operations. What is the impact of the system without any ESINQ factors? A system can support operations in some areas, but not in others.
    - o Is it possible to completely mitigate the ESINQ impacts by adding systems? Some impacts may be able to be completely mitigated, while others may not, regardless of the number of systems.
    - o This assessment aims to bound how each system reduces the impact from the ESINQ factors of interest on each specific modeling factor.
    - o This should be informed to the largest extent possible by the SysML documents, the EEMM, and part B2a, and if complete, the more thorough analysis conducted during TSE6.
    - o Use the value curves to help support the impact assessment, which for mitigation systems like used in this example, should reduce the impact from the ESINQ factors of interest.
    - o This should be assessed by as many SME as possible, leading to an outcome that is acceptable by most.
    - o Are there diminishing returns?

Visualization Tools



Linked Input Factor Modification for System Impacts

1	2					
Linked Input Factors	# of Systems (SmallSats)					
	1	2	3	4	5	6
Ave Time/Det	-2.0%	-4.0%	-6.0%	-8.0%	-10.0%	-12.0%
Pc	0.25%	0.48%	0.68%	0.83%	0.93%	1.00%

- o For Blue Td, I assessed a maximum impact of roughly 2%, without any diminishing returns as additional satellites are added. This accounted for roughly 10% of the impacts from ESINQ degradation seen in part B2a. For Pc, I assessed a 0.25% increase for each additional satellite, but with a diminishing returns factor included. This accounted for roughly 11% of the impacts from ESINQ degradation seen in part B2a.
- o Because this demonstration was looking at the impact of a ISR SmallSat on Blue tanks, in a small protracted fight, the immediate impacts on the force will be relatively small. Thus, the impacts to combat effectiveness is likely small. For other forces, larger forces, and longer battles, these curves could be quite different. It is for this reason that these curves should be done for each agent-system combination.

As shown in Table 61, the synthesis impact assessment is similar to step B2a and directs the user through a somewhat subjective, yet informed process that supports the estimation of system impacts on operational surrogate factors. The key difference is that

the majority of the assessments performed here are based on quantifiable data, primarily the SysML architecture products developed in the execution of the MBSE MEASA. Thus, this assessment is far less subjective than those conducted during ESINQ bounding. Following this analysis, the user can then expand the operational model by including the impacts from the system of interest, bounded by the number of systems. Following the expansion of the operational model to account for the synthesis system, the user can then execute the DOE (TSE3b), conduct analysis (TSE3c), and expand the reference tool for the impacts of the synthesis system. For simplicity, these steps will not be discussed here due to the fact that they are nearly identical to those from parts B2b-c of the IMDP. Following the execution of these steps, a meta-model was developed to provide a mathematical representation of the expected impacts to operational effectiveness from a SmallSat, based on the specified mission set and task organization modeled in the operational model. Following inclusion into the IRCPAT, the meta-model takes the number of SmallSats and the FR as inputs and outputs the expected impact of the system on RCP, which can be added to the overall RCP of the Blue force. For this demonstration, the IRCPAT discussed in Figure 89 was updated to include a single SmallSat to highlight the improvement of RCP, which has been instantiated in Figure 93.

Improved Relative Combat Power Assessment Tool (IRCPAT)

Ratio of Friendly to Enemy							Enemy Forces						
Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total	Number	Strength	Type	F.E.	F.E. Total	External	Ext. Total
42	100%	Armor (M1A2)	10.85	455.70	2.50	105.00	20	100%	Tank (T-80U)	9.20	184.00	0.86	17.20
6	100%	M270-A (MLRS)	10.16	60.96	2.35	14.10	6	100%	Arty-220mm (9P140))	5.25	31.50	0.49	2.94
System Force Equivalent						516.66	System Force Equivalent						215.50
External Force Equivalent						119.10	External Force Equivalent						20.14
Status of External C4I			95%			113.15	Status of External C4I			100%			20.14
ESINQ Effects							ESINQ Effects						
Status of ISR Degradation			50%			-4.32							
External Systems							External Systems						
1	100%	SmallSat (ISR)				0.94							
Friendly Force Equivalent						626.43	Enemy Force Equivalent						235.64
Ratio of Friendly to Enemy 2.658:1							Ratio of Enemy to Friendly 0.376:1						

Hasty Attack			Hasty Defense	
8.2	16.8%	<- Mission ->	36.5%	9.5
		<- Estimated Losses ->		
0.516		<- Estimated % Victory (Curve 1) ->	0.484	
0.553		<- Estimated % Victory (Curve 2) ->	0.447	
0.589		<- Estimated % Victory (Curve 3) ->	0.411	
0.627		<- Estimated % Victory (Curve 4) ->	0.373	

Figure 93. IRCPAT (Application Demonstration: Synthesis)

As shown in Figure 93, following the inclusion of a single ISR SmallSat into the IRCPAT, the overall RCP of the Blue force was increased, resulting in a Blue P_v of 62.7%. This is an increase of 0.3% from the 62.4% seen following the inclusion of degraded ISR. Thus, we have highlighted the ability of the SmallSat to partially mitigate the impacts from degraded ISR, which in this example demonstrates that the ISR SmallSat is capable of mitigating roughly 23% of the 1.3% degradation to Blue RCP. With this short excursion to expand the IRCPAT for synthesis systems complete, let us move back to the TSE application of interest.

d. MBSE MEASA Step 5: Model Analysis

With the operational and synthesis models developed, and the common input factors linked, it is now possible to exploit that linkage to provide better insight into the functionality of the models, specifically with regard to OEM and TSE. However, further

translation of the synthesis system is needed before impacts to combat effectiveness based on physical design changes to the system can be observed in the operational model. To provide more detail regarding this translation, TSE4 through TSE6 will be discussed.

(1) A Linked Model (TSE4)

While common input factors between the operational and synthesis models were established during the execution of the EEMM in parts A as well as TSE1-2, the system's functional architecture has not yet been mapped to these input factors. While we know that the system's impacts will be captured through the manipulation of T_d and P_c, we do not know which system functions impact which model factors, or by how much. This step focuses on establishing these functional linkages as well as bounding their responses. The IMDP TSE4 tab demonstrates the mapping of the system level functions to operational model inputs. While this mapping is somewhat subjective, when bounded by the work in part B2a and supported by detailed SysML documentation and SME interactions, this process can provide extremely valuable insight. As noted by MacCalman et al. (2016), the goal is to map operational inputs to physical inputs either directly, or indirectly using "mathematical expressions, a look-up table with empirical data, or a separate type of model" (3). However, as Beery (2016) notes in his dissertational work, this mapping can also include "heuristics, and regression analysis," which is heavily leveraged in both his and this work.

As directed by the IMDP, synthesis effects mapping was accomplished for each of the system functions identified during the execution of the EEMM. For this demonstration, these functions included providing high resolution ISR capability measured as Ground Sensor Resolution (GSR) and increased visibility (access), and the mapping was accomplished in four basic steps. First, each function was assessed by the user to identify the basic shape of the value curve. Then, this curve was used to estimate the expected response of the surrogate factor, with the expected response bounded by the impact results determined during part B2a. Next, a DOE was executed to build a representative meta-model of the synthesis design parameters and the impact of any change to these parameters on the primary MOE. Finally, a scaling factor was applied to the model to address any potential non-linearity based on the number of systems, which

could include synergistic outcomes as well as diminishing returns. A partial capture of the synthesis MOE mapping matrix for GSR can be seen in Figure 94.

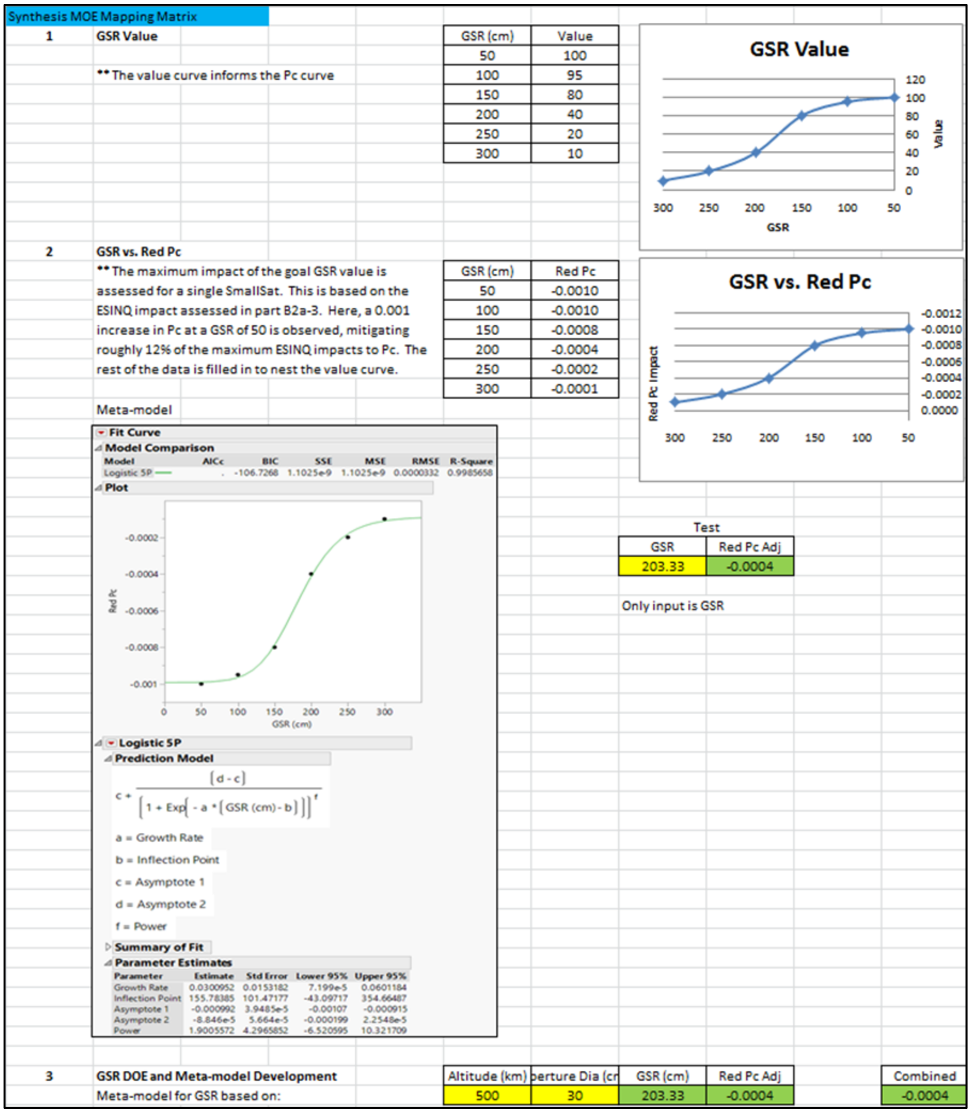


Figure 94. TSE4: GSR Synthesis MOE Mapping Matrix

The resulting meta-model from the GSR mapping matrix captured the effects of synthesis design changes, specifically altitude and aperture diameter, on the primary MOE of GSR, which are represented in the operational model through impacts to P_c. The mapping matrix for access was done similarly and resulted in a meta-model that captures the impact of synthesis design changes to altitude and cone half angle to the primary

MOE of access, represented in the operational model through impacts to T_d. These meta-models provide the linkages necessary to construct a linked model; a description of which is provide by the IMDP and can be seen in Figure 95.

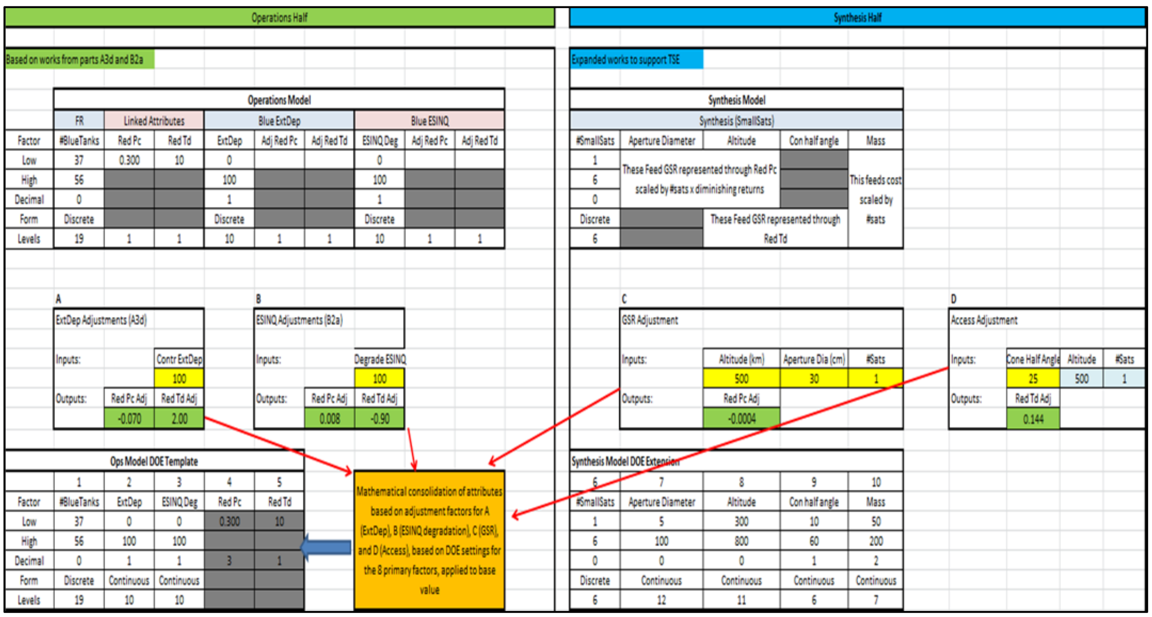


Figure 95. TSE4: Operational and Synthesis Effects Mapping

Following the completion of the MOE mapping matrix for each MOE, the operational and synthesis models can now be effectively linked through meta-models. The four operational and the two synthesis meta-models can be consolidated, and based on the values of the eight primary input factors, the overall impact to Red T_d and P_c can be calculated. With the models linked, it is now possible to execute a DOE to generate the data needed for TSE.

(2) DOE (TSE5)

Execution of the DOE here varies slightly from previous DOEs in two primary ways. First, high resolution designs are encouraged, where saturation of the solution space is imperative to developing a comprehensive TSE. Thus, these designs will be large, bigger than any previous design used throughout the IMDP. Second, there are significantly more steps required to construct the design, primarily due to the linkages of

the operational and synthesis meta-models. Specifically, multiple intermediate mathematical steps will be required to link the input factors and to finalize the design prior to execution. To construct the design, the IMDP directs the user through five general steps. First, the user identifies the primary input factors from both models. This demonstration included three operational inputs (#BlueTanks, BlueExtDep, and BlueESINQDeg) and five synthesis inputs (#SmallSats, AperDia, Alt, Mass, and ConeHalfAngle). In addition to these eight primary factors, two additional effects factors will be calculated based on the values of the eight primary input factors at each DP. These effects inputs included Red T_d and Red P_c, and though used in the final DOE, they are not included in the initial design. The second step is to build the design using the primary input factors. To do so, the MacCalman-2ndOrderNOLH design tool was used, which is available from the NPS SEED Center for Data Farming at https://harvest.nps.edu. Using the 10 factor 2nd order NOLH tab, a design was built that had 365 DPs, with good space filling properties and little correlation between 1st and 2nd order factors. This design was then stacked 10 times to increase saturation, resulting in 3650 DPs; a partial view of which can be seen in Table 62.

Table 62. 10 Factor 2nd Order NOLH Design Tool.
Source: Naval Postgraduate School (2017).

low level	36	0	0	0	5	300	10	50		
high level	83	100	100	6	100	800	60	200		
factor name	lueTanks	ueExtDep	SINQDeg	mallSats	perDiam	Alt	ne1/2Ang	Mass		
	55.42365	5.700549	47.55495	5.700165	45.75865	497.4038	59.46016	148.25	0	0
	37.30412	5.192308	66.51099	0.756593	39.68544	580.3709	12.97527	127.6044	0	0
	63.92885	47.00549	14.31319	4.765879	90.5783	593.8187	45.83654	100.4478	0	0
	39.13247	74.14835	14.03846	3.117198	14.70618	511.7582	27.21291	167.4038	0	0
	41.06799	92.06044	47.43407	3.74011	47.70302	662.5	50.78297	92.89835	0	0
	59.09973	67.43407	100	0.591758	16.00069	415.0687	44.26236	195.0137	0	0
	55.51146	72.75824	24.39286	0.863407	9.410714	305.3571	15.88462	195.9945	0	0
	55.8717	96.45604	73.1044	5.25989	60.62198	789.2033	18.77747	172.4313	0	0
	42.11129	4.972527	34.36813	0.781978	35.45742	429.2582	36.98214	168.3516	0	0

The third step focuses on building out the remainder of the design, accounting for Red T_d and Red P_c. To do so, the full 3650 DP design was copied to a clean spread sheet, and six new columns were created for each of the adjustment factor meta-models. These included the four operational adjustment meta-models that would represent the impacts of external dependencies and ESINQ degradation, as well as two synthesis adjustment meta-

models, which would represent the impacts from design changes to the five system attributes. These meta-models were applied to each DP, and their values were calculated based on the values of the eight primary factors at each DP. In the fourth step, two consolidation columns were added for T_d and P_c. Because the adjustment factors were all designed as modifications to the base value of either T_d or P_c, the summation and consolidation of the six adjustment factors for each of the two effects factors was possible at each DP. Finally, the last step was to clean up the design by removing the mathematical intermediate steps used to link the effects factors. Following this housekeeping, the final 10 factor design was achieved, including eight primary factors and two effects factors, as shown in Table 63.

Table 63. Final 2nd Order NOLH Design

	Ops Model Inputs				Synthesis Model Inputs				Unused
Primary Factors								Effects factors	
#BlueTanks	BlueExtDep	ueESINQDe	#SmallSats	AperDiam	Altitude	oneHalfAng	Mass	Td	Pc
55	6	48	6	45.8	497.4	59.5	148.3	10.8	0.299
37	5	67	1	39.7	580.4	13.0	127.6	9.8	0.301
64	47	14	5	90.6	593.8	45.8	100.4	11.6	0.267
39	74	14	3	14.7	511.8	27.2	167.4	11.9	0.251
41	92	47	4	47.7	662.5	50.8	92.9	12.3	0.239
59	67	100	1	16.0	415.1	44.3	195.0	10.5	0.260
56	73	24	1	9.4	305.4	15.9	196.0	11.4	0.251
56	96	73	5	60.6	789.2	18.8	172.4	12.3	0.238
42	5	34	1	35.5	429.3	37.0	168.4	10.1	0.298
45	17	29	1	94.2	541.4	37.4	55.9	10.5	0.289
65	93	8	3	49.1	580.1	17.0	190.2	12.0	0.235
83	31	27	3	84.0	596.3	18.0	99.1	10.7	0.280

For the operations model, only #BlueTanks, T_d, and P_c were adjusted for each DP, with Blue P_v being the primary output. For the synthesis model, #SmallSats, AperDia, Altitude, ConeHalfAngle, and Mass were used, with GSR, access, and cost being the primary outputs. The two unused factors were needed to establish the impacts of the effects factors and were needed again during TSE. Following the development of the design, it, the study files, and the models were submitted to the NPS Advanced Computing Cluster for execution, where each of the 3650 DPs was replicated 200 times, for a total simulation run of 730,000.

(3) **Analysis and TSE (TSE6)**

After the models were executed, the output data from both models was consolidated with the original design before analysis could be conducted. This data included one output factor from the operations model (P_v) and three output factors from the synthesis model (GSR, access, and cost). This was a fairly straight forward process, but care was taken to ensure that the output data from both models was applied to the correct DP in the design. Following the addition of the output data, the spreadsheet was cleaned up for future analysis. For JMP, this housekeeping required some translation and scaling of certain input factors to put them back into their original form. Additionally, the two effects columns (Red T_d and P_c) were removed. While they were needed to execute the design, their impacts were now being captured by the four primary MOEs and thus, were removed to reduce the complexity of the analysis. A screenshot of the analysis spreadsheet following output consolidation can be seen in Table 64.

Table 64. TSE Analysis Spreadsheet

Input Factors								Output			
Primary Factors								Ops Outpu	Synthesis Output		
#BlueTanks	BlueExtDep	ueESINQDe	#SmallSats	AperDiam	Altitude	oneHalfAng	Mass	Pv	GSR	Access	Cost
55	6	48	6	46.0	497.0	59.0	148.0	0.875	1.32	50.3	$200,241,132
37	5	67	1	40.0	580.0	13.0	128.0	0.26	1.77	0.07	$83,146,296
64	47	14	5	91.0	594.0	46.0	100.0	0.995	1.23	13.43	$99,212,936
39	74	14	3	15.0	512.0	27.0	167.0	0.535	4.16	3.39	$143,268,680
41	92	47	4	48.0	663.0	51.0	93.0	0.63	1.69	41.8	$116,431,634
59	67	100	1	16.0	415.0	44.0	195.0	0.955	3.16	2.85	$97,199,199
56	73	24	1	9.0	305.0	16.0	196.0	0.92	4.13	0.05	$97,419,976
56	96	73	5	61.0	789.0	19.0	172.0	0.935	1.58	4.33	$200,162,265
42	5	34	1	35.0	429.0	37.0	168.0	0.455	1.50	1.93	$91,353,737
45	17	29	1	94.0	541.0	37.0	56.0	0.635	0.70	3.09	$65,255,975
65	93	8	3	49.0	580.0	17.0	190.0	0.985	1.44	0.85	$156,858,515
83	31	27	3	84.0	596.0	18.0	99.0	1	0.86	1.15	$106,134,574

Once the data was organized, it was then imported into a JMP data table for analysis. For this demonstration, a standard least squares regression was used to conduct effects screening. Specifically, this regression used a factorial to the 2^{nd} degree and polynomial to the 2^{nd} degree of the eight primary factors, while using the means of all four outputs as the role variables. Following the regression, intermediate level analysis was conducted to verify the usability of the output data for TSE. While this analysis will not be discussed here, it was done similarly to the analysis seen throughout this

dissertation and included investigation of solution space saturation, inspection of the quality of fit, ANOVA, inspection of significance, and inspection of response directionality and conformity. Following the intermediate analysis of the data, which verified the usability of the output data in this demonstration, the contour profiler was then used to execute TSE, which can be seen in Figure 96.

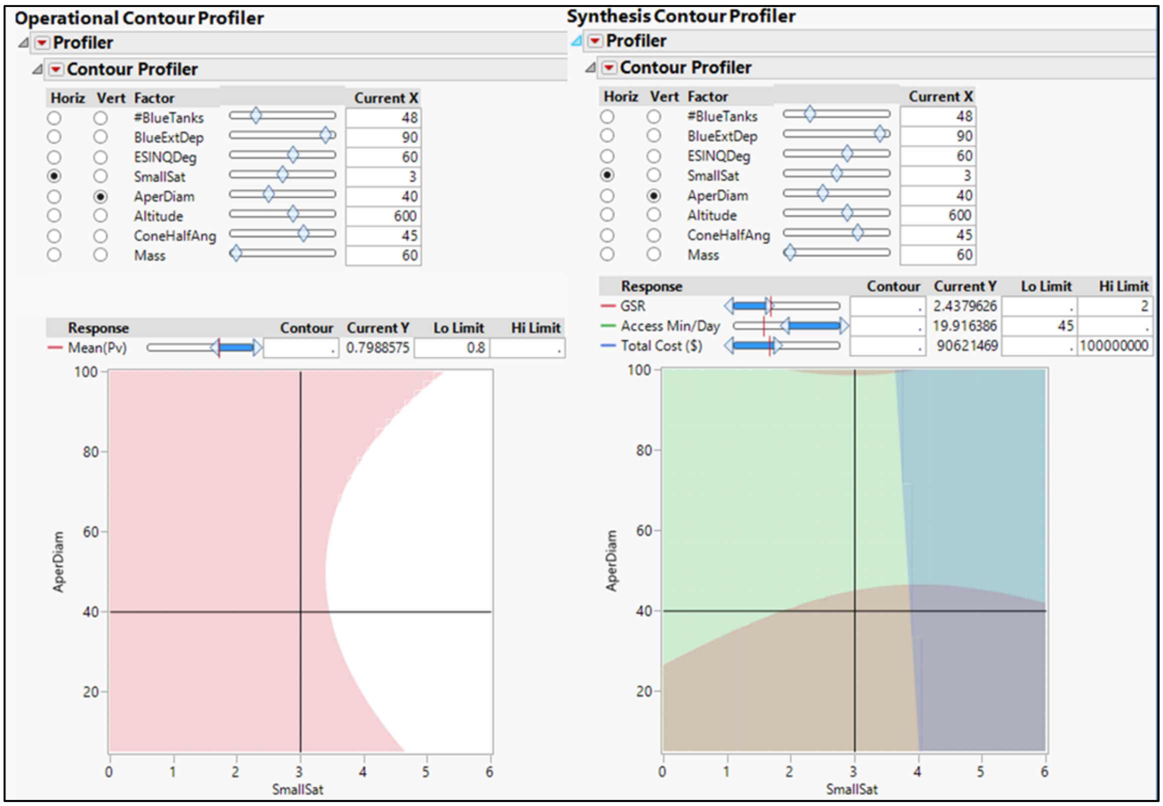


Figure 96. TSE6: Analysis (Contour Profiler-1)

Using JMP, a contour profiler was set up to simultaneously observe the operational and synthesis modeling factors and their associated MOEs. On the left side, we see the operational profiler, where operational inputs can be manipulated, constraints on the responses established, and impacts of these decisions observed with regard to the linked operational and synthesis MOEs of interest. On the right side, the reciprocal is seen with the synthesis profiler, where synthesis input factors can be manipulated, their responses bounded, and the impacts of these decisions on operational and synthesis

MOEs observed. Using this tool, it was possible to explore the system trade space and build a better understanding of the system and to gain insight into how design choices can impact operational effectiveness. With the operational and synthesis factor settings selected in this demonstration, we can see that there was not a feasible solution; the resulting system configuration failed the meet the minimum acceptable P_v noted in the operational responses, as well as failed to meet the minimum GSR and access requirements noted in the synthesis responses. To demonstrate the utility of this tool to support TSE, let us explore the system trade space in an attempt to address the questions posed in the scenario at the beginning of this section. These questions were as follows: First, the Army asked for an estimation of the expected impacts of a SmallSat on operational effectiveness. Second, the Army asked how many of these systems would be needed to mitigate the impacts from a moderate level of ISR degradation, and what the potential cost of these systems would be. Starting with the first question, the TSE tool was modified to remove all degradation, setting external dependencies to 100% and ESINQ degradation to 0%. Then, using a single satellite, the synthesis attributes were modified until a moderate “middle-of-the-road” solution was achieved; the TSE tool for which can be seen in Figure 97.

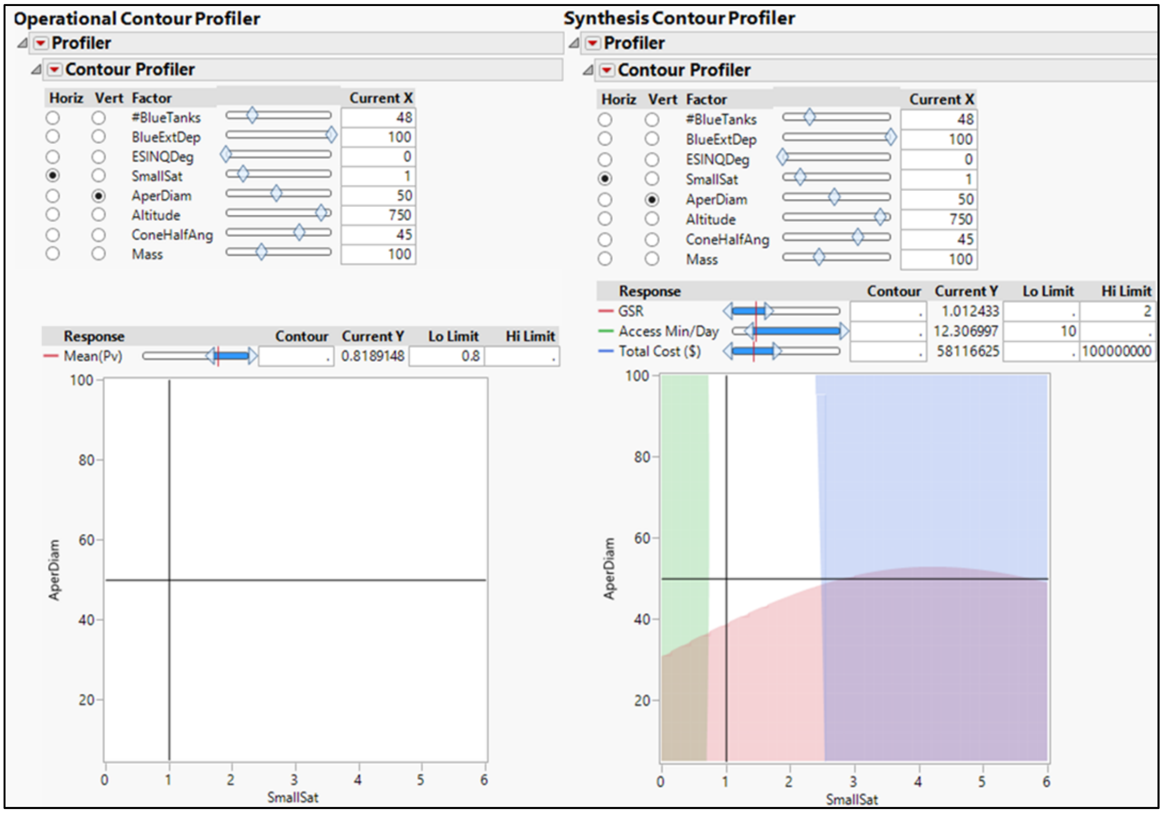


Figure 97. TSE6: Analysis (Contour Profiler-2)

This solution had a fairly low cost of $58.1 million, which was toward the lower (better) bound of the ranges used; had a good GSR of 1.01m, which was also toward the lower (better) bound of the ranges used; and provided a total access of 12.3 min/day, and while this was toward the lower (worse) bound of the ranges used, was still acceptable. While this solution was not weighted for any of the four MOEs, which is typically seen during system design, it provided a fairly robust solution given the lack of details for this question. With these system attributes, the single SmallSat was shown to provide an average of a 0.26% increase in P_v across the range of FRs. This impact was more apparent at higher FRs and insignificant at lower FRs, which is understandable when considering the cumulative contribution of ISR to the warfighter. Thus, in addressing the first question, the estimated impact to operational effectiveness from a SmallSat is on average roughly 0.3%. In reality, the better answer is that the impact depends on both the design of the SmallSat, its implementation, the mission, the size of the force, and a host

of other factors. Nevertheless, the tool was capable of providing a quantifiable answer that has otherwise gone unaddressed in modern acquisitions.

Next, the second question was considered. Here, the middle-of-the-road satellite design was abandoned, and the system attributes were modified to maximize the potential of a single SmallSat to mitigate a moderate level (50%) of ISR degradation while minimizing the number of satellites. Thus, P_v was the primary metric used during TSE, and following the iteratively manipulation of the tool, a system design was identified that maximized the contribution to P_v from a single satellite. Then, the number of satellites was increased until the 50% ESINQ degradation was overcome, which in this demonstration required four SmallSats. Finally, because there was still tradespace in the design, the system attributes were further refined to maximize the utility of the remaining MOEs while ensuring that the ESINQ degradation continued to be mitigated. This example focused on maximizing GSR and access, while reducing cost and complexity. And while this additional manipulation was not necessary to address the question, the step was implied when the Army stated that it wanted to maximize the attributes as much as possible. The TSE tool following these modifications can be seen in Figure 98.

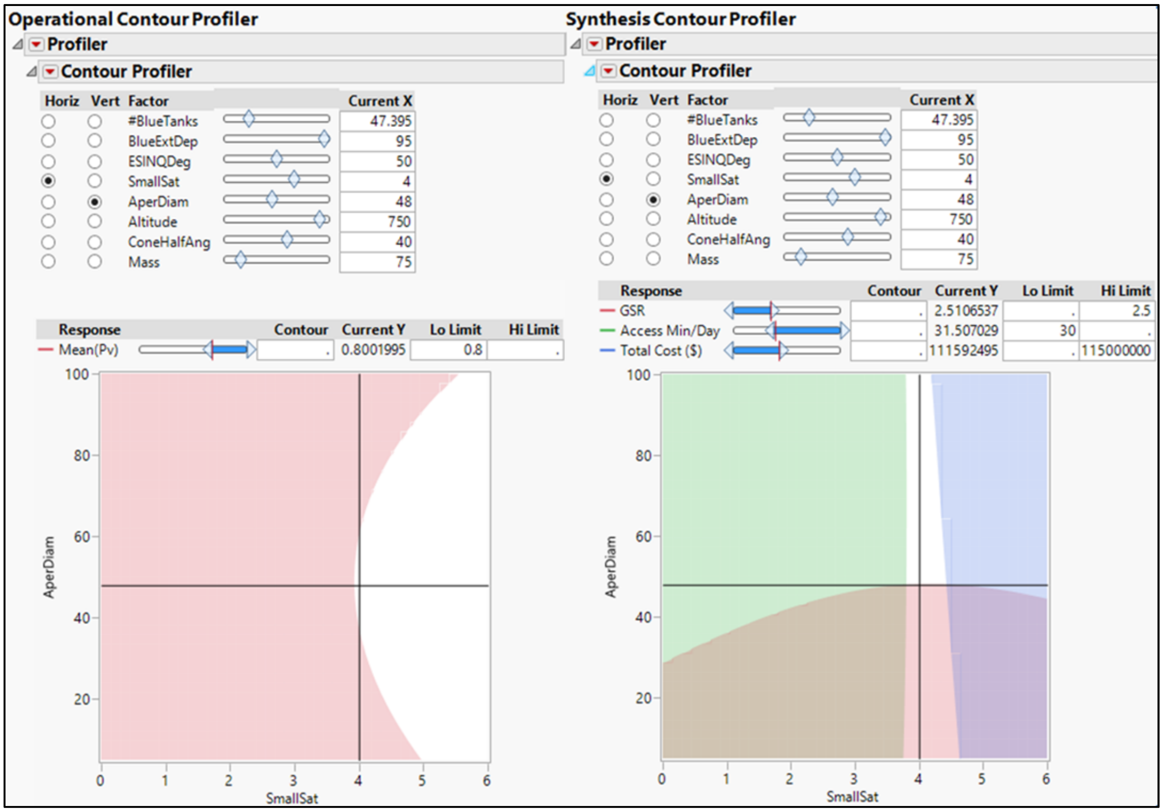


Figure 98. TSE6: Analysis (Contour Profiler-3)

As shown in Figure 98, using these operational and synthesis attribute settings; a feasible design solution was obtained that met both the operational and synthesis MOE requirements. Thus, in addressing the second question, the resulting solution met the Army's primary requirement of mitigating a 50% degradation of ISR collection assets through the use of four ISR SmallSats. These satellites each had a GSR of 2.51m and provided a total access time of 31.5 min/day, at a total cost of $111.6 million. While this question was again very specific, it highlights the power of the TSE tool to support acquisitions decision making, giving the user the capability to assess the impacts from design changes on operational effectiveness.

3. Discussion

The power of acquisitions decision support tools to effectively link operational and synthesis models is clearly articulated in modern works, and as described here, provides users an extremely flexible TSE tool for investigating system design

considerations and the resulting impacts to operational effectiveness. By applying the outcomes of the IMDP, the TSE tool was expanded, and through integration of the meta-models that could account for external dependencies as well as the impacts from ESINQ effects of interest, a more complete TSE tool was developed. This expansion of the tool gave more utility to the user, and allowed for a more accurate assessment of not only the operational impacts from degradation, but the potential contributions of emerging systems to mitigate these impacts as well.

C. SUMMARY

The primary contribution from the execution of the IMDP was the development of meta-models that describe the impacts from ESINQ effects on metrics of operational effectiveness. This chapter demonstrated a few potential applications of these meta-models, specifically with regard to improving operational and acquisitions decision support tools. First, the meta-models developed during the execution of the IMDP were applied to an operational decision support tool. During this demonstration, the IRCPAT was improved to account for all four of the potential sources of combat power. This expansion allowed the tool to account for and quantify the contributions to RCP from external dependencies and ESINQ effects, which yielded a more insightful planning tool. Next, these improved models were used to provide a more complete and accurate representation of the OE during TSE, and as before, resulted in a more insightful exploration of the common operational and synthesis trade space. The contributions of this work were made possible by the ability of the IMDP to support the construction of better models. When these models were used as foundational elements in other decision support tools, the overall accuracy of these tools was improved. This improvement was largely due to the underlying models' increased accuracy at representing the OE and their ability to account for all four sources of combat power, specifically through addressing the external dependencies and ESINQ effects so routinely ignored in traditional MDPs.

VI. CONCLUSIONS AND FUTURE WORK

While the utility of space systems and threats from adversary counter-space capabilities are well understood, neither space systems nor threats can be easily measured; thus, they are typically ignored during the MDMP because they are considered non-quantifiable. Unfortunately, it is this perception of space-based capabilities and other external force multipliers as non-quantifiable that lies at the root of the problem. While ESINQ effects may be difficult to quantify, they are by no means non-quantifiable; up to this point, there has simply been no formal effort within the community to quantify them. By moving away from the consideration of external force multipliers like space-based effects as non-quantifiable, and rather, consider such effects as ESINQ, a more accurate representation of these effects can be captured in the referent. This improved referent addresses the possibility of quantifying the impacts of these effects while still highlighting the difficulty in doing so.

The fundamental issue with traditional MDPs is that the underlying assumptions and methods for gathering data during the model definition steps, specifically during the development of the referents, are flawed. Thus, the models developed fail to represent the OE and the systems they were intended to model, resulting in a more incomplete and inaccurate analysis. To address the inability of traditional MDPs to account for the contributions from external dependencies and ESINQ effects, an improved and more flexible MDP was needed that enabled the inclusion of more than the two primary referent contributors. By focusing on improving the underlying MDPs to account for ESINQ force multipliers, it was possible to produce better models, execute more informed OA, and develop more complete decision support tools, which in turn should result in better decisions regarding preparation for operations in a D3SOE. This work expanded the M&S body of knowledge through the development of a formalized methodology to account for and bound ESINQ factors and effects within the MDP. The IMDP developed in this work addressed the lack of synergy in traditional MDPs and translated this improved understanding to a set of operational and acquisitions decision support tools that support the quantification of the impacts from ESINQ effects.

A. CONCLUSIONS

In this dissertation, we presented a proof of concept that enabled operational models to account for and quantify ESINQ factors and effects. This work demonstrated that when applied to traditional MDPs, the IMDP improved model definition and development, the two primary steps of most traditional MDPs. The result of this improvement enabled users to gain novel insights into the workings of the model and account for the external dependencies and ESINQ factors and effects that had mostly gone unaddressed. This research clearly demonstrated the ability of the IMDP to augment traditional MDPs to address a broader array of potential impacts to operational effectiveness than previously possible. The IMDP complements traditional MDPs by formalizing a methodology for expanding the model definition step to account for ESINQ effects of interest in the referent. Through the use of the IMDP, a more accurate representation of the OE can be implemented in the model, greatly improving the model's fidelity and ability to link a system's characteristics — to include inputs from external dependencies and ESINQ effects — to metrics of operational effectiveness. The contribution of the IMDP to the M&S body of knowledge can best be captured by considering its application to traditional MDPs as seen in Figure 99.

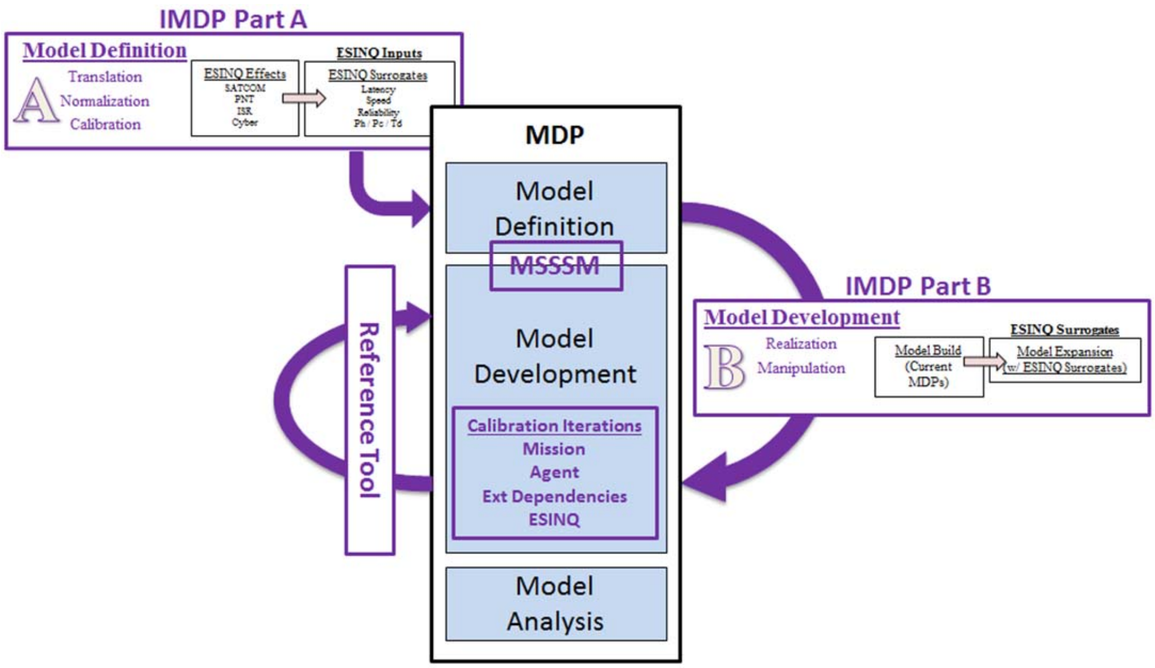


Figure 99. IMDP

The IMDP developed in this work provides two primary advancements when used in conjunction with traditional MDPs: first, was the ability of part A of the IMDP to address the lack of synergy in traditional MDPs, specifically during the model definition step. By expanding the potential input sources from two to four, and then codifying the process for translating, normalizing, and calibrating the expected impacts that these contributions have on the operational model, a broader more holistic approach of defining a model's referent was achieved. Second, part B of the IMDP formalized a methodology for implementing the improved model definition achieved during part A within the operational model. Through an iterative implicit modeling process, the ESINQ-enabled operational model was realized, and then manipulated through the modification of surrogate factors to capture the impacts from ESINQ effects. Not only did these expansions improve the utility of traditional MDPs, they resulted in a better understanding of the impacts of ESINQ effects on operational effectiveness, which supported a more holistic and complete understanding of the OE. Through the formalized definition of an IMDP, this work provided M&S users a new tool set for addressing

ESINQ and other “soft” factors that do not fit well into traditional MDPs, addressing many of the M&S community gaps discussed in Chapter II.

In achieving this primary contribution, this work produced five secondary contributions that can have an immediate impact within the M&S community. These contributions addressed a significant portion of the organizational gaps addressed in Chapter II, and can better support the U.S. military as it prepares for operations in a D3SOE. First, the IMDP formalized a MSSSM, and provided users a far more robust methodology for screening and selecting potential M&S packages for use in simulation studies. While a slight offset from the primary contribution of this work, the author found the lack of any formalized process for selecting an appropriate M&S package within the M&S community literature established the need for the development of the MSSSM. By providing users a framework for executing a more complete and logical investigation of available M&S packages, the likelihood of selecting a more appropriate M&S package for use in an M&S study has been increased.

Second, the IMDP supported the development of an ESINQ-enabled operational model which can capture the impacts of ESINQ effects on operational effectiveness. While these effects are typically considered non-quantifiable and ignored in traditional MDPs, the IMDP allows model developers to address them, and thus, represent a more complete and realistic understanding of the OE. This expanded view of potential operational model inputs gives users the flexibility to explore ESINQ factors like space and cyber, to name only a few, and to gain insight into the potential impacts they may have on operations.

Third, the IMDP, supported by DOE and statistical analysis, enabled the quantification of the impacts of ESINQ effects within the operational model, and thus, supported the development of surrogate meta-models. These meta-models can be used to represent the impacts of ESINQ effects in terms of impacts to operational effectiveness, and once developed, can be transferred and implemented within other models and tools to improve their accuracy.

Fourth, by applying the ESINQ-enabled meta-models, the primary operational support tool used by the Army was updated and improved. The IRCPAT developed in this work is a significant improvement over the current tool, the FRC, and greatly improves the utility and flexibility of the tool in support of operational planning. The IRCPAT allows the user the flexibility to address and account for external dependencies, ESINQ effects, and external systems when determining the overall RCP. By accounting for a more complete assessment of the contributions to RCP, the IRCPAT should reduce the underestimation of RCP that was so typical of the FRC.

Fifth, by linking the ESINQ-enabled operational model to a synthesis model of an emerging system, this work was able to demonstrate the potential of developing improved acquisitions support tools that could better link system design decisions to metrics of operational effectiveness. By using an ESINQ-enabled model, acquisition professionals can make a more accurate assessment of an emerging mitigation technologies' capacity (whose contributions can be considered ESINQ effects) to improve RCP. Thus, a more direct linkage between design choices and impacts to operational effectiveness were made, which better enforces the concept of OEM.

This dissertation fills some significant gaps by enabling traditional MDPs to capture ESINQ effects. By providing a methodology that can achieve a better representation of the OE in the referent, model developers can bound ESINQ effects within a model. This more complete understanding of the OE will improve the models developed through traditional MDPs; will improve the assessments generated from their analysis; and support more informed decisions regarding both the use and allocation of resources. Together, these improvements will better address the gaps described in Chapter II, and support the United States to make more accurate and informed decisions as we "prepare" for operations in a D3SOE.

B. FUTURE WORK

This research was the logical expansion of the work of others, specifically MacCalman and Beery, who improved and refined their respective MBSE analysis methodologies to achieve a more complete and robust TSE. While this work was a proof

of concept, it demonstrated the capacity of the IMDP to improve the accuracy of the underlying models by capturing a more accurate representation of the OE, and thus, making it possible to improve current operational decision support tools as well as execute a more refined TSE. While there are countless potential areas for future work, it is the author's belief that the following areas offer the most promise for expanding this work and continuing to improve the M&S and MBSE bodies of knowledge.

The first area of expansion deals with the use of genetic algorithms to reduce the complexity and resources needed to execute the IMDP. While the author originally considered the use of genetic algorithms, the uncertainty at the time regarding the potential dimensionality issues of the solution space led to a more conservative approach. In this approach the author used large designs in an iterative manner to support a systematic investigation of the solution space, and while less efficient than genetic algorithms, it reduced the uncertainty regarding dimensionality. Regardless, following the completion of this research, the author is now confident that some efficiency can be gained through the use of genetic algorithms, and believes that they have the potential to significantly reduce the resources required to execute the IMDP.

The second area of expansion deals with the use of the IMDP to investigate other ESINQ effects. While the demonstration and application of the IMDP outcomes of this work focused on space-based effects, there are a significant number of other ESINQ effects that merit detailed investigation. Such investigations could look at cyber, moral, leadership, and information warfare, to name just a few, and then apply that knowledge to expand and improve operational and acquisitions support tools. Yet, due to the broad distribution of ESINQ effects across numerous potential domains, it is also possible that the implementation of the IMDP could need adjustment. Thus, it is well worth the effort and resources to test the IMDP across a broader range of ESINQ effects, and if necessary, modify the IMPD to support the inclusion of this expanded understanding.

The third area of expansion deals with the application of the IMDP to formalize the process for accounting for ESINQ factors within synthesis models. While the author originally had intended to apply the IMDP to both operational and synthesis model development, synthesis modeling was eventually considered outside the scope of this

work and not addressed. Nonetheless, it is the author's belief that, like operational models, the application of the IMDP during the development of the synthesis model, specifically the model definition steps, should produce a more accurate model, yield better insights into the system and its interactions, and support more informed decisions.

The fourth area of expansion deals with improving the resolution and accuracy of the underlying models. While this work served as a proof of concept and used relatively low resolution operational models to demonstrate and apply the outcomes of the IMDP, future expansion of this work should focus on developing a more robust model. This expansion should include:

- Better source data, specifically an improvement to the COFM/FA-SWN used in this work, to include the use of classified data.
- Better combat models. While MANA was sufficient for the purposes of this work, the author believes that, with more resources, there are far better models to which the IMPD can be applied.
- Better reference tools. Like the model, a better reference tool can provide more resolution in the analysis following the implementation of the IMDP.
- Different, longer, and more detailed scenarios. While the scenarios used in this work were fairly simple, there are significant advantages to expanding the size and the scope of the scenarios used in the model.

The fifth area of expansion deals with the investigation of time, specifically the impact that time can have on ESINQ effects with respect to operational effectiveness. While this work focused on relatively short duration operational scenarios, which generated relatively small ESINQ impacts to operational effectiveness, the author asserts that the responses observed in this work are not only non-linear, but almost certainty have a non-linear third dimension aspect as well. While the demonstration in Chapter IV showed less than a 2% decrease in P_v due to ISR degradation, the author believes that this impact would be far greater had the ISR degradation been active for a much longer period of time prior to the execution of combat. Thus, the author suggests that the impact of ESINQ effects be investigated over time, and a third dimension factor be added to the ESINQ-enabled meta-models to account for the change in the response that results from the length of time that the ESINQ effect is active.

The sixth and final area of potential expansion deals with the use of a more robust TSE tool. While this work used JMP to create a set of contour profilers that allowed the author to demonstrate the potential for linking ESINQ-enabled operational models to synthesis models to conduct a more thorough TSE, this demonstration was fairly simplistic and ignored a sizeable portion of the investigations typically done during analysis of emerging systems. Thus, this work has only provided a glimpse into the potential of the IMDP to improve TSE. To better articulate the advantages of using ESINQ-enabled operational and synthesis models during TSE, the author suggests the use of a more robust TSE tool, one that can provide a more holistic SE approach to systems and trader-off analysis.

APPENDIX A. MSSSM

The purpose of this appendix is to address the first of the supporting research questions as outlined in Chapter I. This question reads: What models are capable of representing the contributions from external dependencies and ESINQ effects, and to what level of resolution? By addressing this question now, in detail, using an organized and detailed evaluation process to investigate potential M&S packages, I will be able to justify my final choice for an M&S package used during this dissertation. Yet, no formal process for screening or the selection of M&S packages exists, so the MSSSM was created to fill this gap, the steps of which can be seen in Table 65.

Table 65. MSSSM

Part A1c (MSSSM)		
Investigate Models and identify a Model with appropriate factors which can best model the tangible impacts from Step B, that can be used as surrogates for the intangible effects.		
A	Develop the M&S Operational Concept	
B	M&S Review and Screening	
C	Initial Screening	
D	Secondary Screening	
	1	Considerations
	2	Secondary Screening
E	Model Exploration (for each remaining M&S package)	
	1	Initial Observations
	2	Potential Input factors for Representing ESINQ effects
	3	Potential Output responses for operational effectiveness
	4	Model development
	5	DOE
	6	Analysis
	7	Findings
F	M&S Comparison and Evaluation	
	1	Modeling ESINQ
	2	Usability
	3	Flexibility
	4	Support
	5	DOE
	6	Analysis
	7	Agent Behavior
G	Conclusion and recommendation	
H	Application (EEMM)	
	1	Map the potential surrogate factors you will be using to represent the ESINQ effects you are investigating to the expected impacts identified during part A1b.
	2	List the final surrogate input factors you will be modifying to represent your ESINQ effects following your analysis. Remember, the less factors the better as long as you can represent all the effects and impacts you are trying to capture.
	3	Transfer the selected surrogate factors back to the EEMM

A. THE OPERATIONAL CONCEPT

In most conceptual design and early phase development processes, it is often best to start with an overarching concept that will document how the system is expected to act, its intended application, how it is expected to be integrated, its expected inputs and outputs, and how it will be used. In SE, this document is called the OC. The development of a model is no different, and thus, the creation of an OC is a natural starting point. The creation of the OC used in this work was accomplished by addressing a number of key questions regarding how well a potential M&S package meets specific requirement considerations as outlined in the OC. These question are very similar in function to what Middleton (2010) calls his "Terms of Reference," which he developed in conjunction with Dr. George Mastroianni in 1996 to provide users a framework for understanding the problem prior to the selection of a model. The MSSSM starts at this same point, but takes this framework further by providing an explicit methodology that takes a user completely through the screening and selection process. For this work, the following questions were used to form the body of the OC when evaluating potential M&S packages.

1. What are we trying to investigate?

For my research I am primarily interested in the development of an acquisitions decision making support tool, and secondarily, the creation of an operational support tool in order to provide better information to support better operational and resourcing decisions. These tools will tie synthesis and operational design tradeoffs of emerging space systems with impacts to combat effectiveness. Thus, I need a combat model that is capable of providing data capable of quantifying decision impacts to measures of combat effectiveness within the context of a D3SOE.

2. What types of studies are you interested in (Live/Virtual/Constructive)?

Simulations can be broadly broken into three primary groups: Live, where real people use real equipment; Virtual, where real people use simulated equipment; and Constructive, where simulated people use simulated equipment. Because my tools will require the use of meta-models in order to more accurately account for uncertainty, I will require a significant number of simulation runs to fully explore the tradespace. Coupled

with the fact that I have limited time and resources available to me as a student and researcher, I will only be considering constructive simulations. While Live and Virtual M&S tools have potential merits with respect to my work, they are heavily dependent on levels of human integration and time that is beyond my capacity to provide.

3. What is the purpose of the study (Descriptive/Prescriptive/Predictive)?

This will be a mixed methods study, where I will be interested in all three study purposes. I am interested in the descriptive nature of the model to allow me to gain novel insight and quantify the potential impacts from a D3SOE and potential mitigation strategies, which will support operational planning and support. I am interested in the prescriptive nature of the model to allow for comparisons between competing technology alternatives, which will support acquisition decision support. And finally, I am interested in the predictive nature of the model to allow for the anticipation of operational impacts from adversary counter-space activities, which will support operations and planning.

4. What are the desired factors, responses, MOPs, MOEs?

A factor is simply a user's input into a model, or the settings that establish the initial conditions of the simulation. The responses on the other hand are the outputs from the M&S following its completion. Looking at this from the perspective of OEM, my primary evaluation metrics or MOEs will be in the form of measures of combat effectiveness. Thus, I will need an M&S package capable of accepting combat related input factors and noise factors, and then output combat related responses from the perspective of ground forces. Any M&S package that takes in user factors related to combat, attrition rates, probabilities of kill, hit, detections, etc., and then outputs responses like casualties, length of battle, communication effectiveness, shooter-targets stats, ect, is preferred over M&S packages that have less intuitive responses.

5. What level of the model hierarchy do you want?

The purpose of this work is to try to evaluate emerging space systems and their capabilities to mitigate impacts to combat effectiveness due to a D3SOE. I am attempting to do this all within the context of the OE described in the recently published AOC. Thus, I am looking for a combat model that can accurately model ground combat operations at

the Battalion to Brigade level, which is reliant on reach back support from communications and space. Therefore, a mission level model is most appropriate for this dissertation. While one could argue that a Theater level model is also valid, these models tend to be more deterministic, less detailed, and more complex than what I need for this work.

6. Do you need a deterministic or a stochastic model?

As always this should be based on the intended needs, wants, interests, and requirements of the stakeholders. A deterministic model is one where variability and uncertainty are ignored. These are typically simpler, good for point estimates, and more controllable. Stochastic models on the other hand take in account uncertainty and variability, where a given set of inputs will produce a range of outputs along some distribution to account for randomness. Because I am looking for a combat model that can accurately quantify combat and the impacts to combat effectiveness, coupled with the fact that combat by nature is inherently chaotic, a stochastic model is appropriate.

7. What level of resolution (Low to High) is needed?

Resolution is simply the degree of detail or fidelity of the model. The higher the resolution the more accurately it represent the real world, but at the cost of increased complexity and resource requirements. Because this is a proof of concept, and time and resources are limited, I will be looking for a relatively low resolution model. While not as accurate in its representation it will meet the intent of this research and can be expanded upon in the future with I higher fidelity model.

8. What are the requirements for VV&A?

VV&A establishes the fitness and credibility of an M&S for a specific purpose and use. Because I am not developing an M&S, verification is not considered, but Validation and Accreditation should be addressed because my VV&A requirements will impact the number of potential M&S packages. Because this is a proof of concept, with the intent to develop a method and set of tools for supporting operational and acquisitions decisions making, I do not need the model to be VV&A. While it would be beneficial, it is not required at this juncture, and as long as the selected M&S meets face validation it

will meet my intent for this research. In the future the methodology and tool set provided by this work can be expanded to incorporate a VV&A model.

9. Do you need a Time-Step or a Discrete Event model?

Both Time-Step and Discrete Event (DE) are methods of time advancement within a simulation. Time-Step models advance the simulation clock by a fixed increment, at which time the states of all agents are updated. These are more intuitive, but can be computationally excessive and they induce anomalies and artifacts due to the size of the time step. DE models advance time to the time of the next event in the event list, at which time the states of just that event are updated. These are far more efficient, requiring far less computational power, but complexity increases with the number of agents and interactions. Because neither of these impact the ability of an M&S package to meet my needs both are valid options at this point, so I will ignore it as a screening factor.

10. What type of output and results are needed?

Again, I am interested in the output of the simulation, specifically how a given set of input factors affect the output response in terms of ground combat operations. But, because I mentioned that I will need to perform face validation, I will also be interested in the behaviors of the M&S as the simulation progresses. So, I will need an M&S package that is capable of producing outputs in terms of measures of combat effectiveness that also gives me visibility inside of the simulation as it unfolds. This typically means a time-step model, but there are DE models available that allow users to visualize the model as it unfolds.

11. What level of classification is needed?

To simplify the complexity of the problem, and for ease of research, publication, and model selection, I will be doing this dissertation at the UNCLASSIFIED level. While this will likely not accurately quantify the number of adversary threat capabilities and friendly mitigation capabilities, there is enough information available at the unclassified level to accurately capture the full range of potential effects needed to complete the proof of concept, and develop an acceptable methodology and tool set. Future expansions of this work should use higher levels of classifications in order to more accurately (reduced

variability) represent the impacts to operations from adversary use of counter-space capabilities.

B. M&S REVIEW AND SCREENING

In order to develop a set of potential M&S packages, I started my assessment by doing a broad investigation of all M&S packages that were currently available, either through NPS, service M&S organizations, or the DOD M&S Catalog. I defined the term "available" as any M&S package that Army planners could get access to and utilize for planning and experimentation, without cost. At this early juncture, I was more inclusive than exclusive and included any and all M&S packages that looked as if they could be modified for my purposes as outlined in the OC, without constraints. My investigation uncovered the M&S packages described in Table 66 that at first glance looked as if they could meet my needs.

Table 66. Potential M&S Packages

			DoD M&S Catalog										
NPS			AF Space					Army Training				AF	Army
MANA	JDAFS	OSM	SEAS	SCT	SB	SIAM	Guardian	JCATS	AWARS	JTLS	One SAF	AFSIM	COMBATXXI

As shown in Table 66, my initial investigation uncovered fourteen potential M&S packages, which are roughly organized by source and then by purpose. The majority of the packages came from the DOD M&S Catalog, with AF Space and Army Training models accounting for the majority of them. I looked at each of the fourteen M&S packages in a little more depth to explore the potential of each to meet my research needs, and a brief synopsis of each potential M&S package follows.

1. MANA (Map Aware Non-Uniform Automata)

MANA is an agent-based model that was developed to conduct military OA, specifically focusing of COA and tradeoff analysis. MANA was developed around two key ideas: First, "that the behaviour of the entities within a combat model (both friend and foe) is a critical component of the analysis of the possible outcomes. [Second], that we are wasting our time with highly detailed physics-based models for determining force

mixes and combat effectiveness" (McIntosh et al. 2007, 2). MANA is of interest because of its focus on the impacts of communications, sensors, and SA on combat effectiveness.

2. JDAFS (Joint Dynamic Allocation of Fires and Sensors)

JDAFS is a low resolution DE modeling framework that provides users a nearly unlimited amount of modeling freedom. JDAFS was developed to support users in "situations requiring fast turnaround analysis and those requiring much flexibility and customization on the part of the model" (Buss and Ahner 2006, 4). Because it is a framework, it is possible for users to add in almost any functionality required, but at a cost of development time and complexity.

3. NPS-OSM (NPS-Orchestrated Simulation through Modeling)

OSM is a DE simulation model currently in development by the SEED Center at the NPS using the Orchestrated Simulation through Modeling (OSM) modeling and simulation framework. The focus of NPS-OSM has been on modeling maritime maneuver and combat, but currently the model is still fairly immature, with no ground combat capability and no explicit communication or BMC2 functionality.

4. SEAS (System Effectiveness Analysis Simulation)

SEAS is a constructive agent-based combat model framework that focuses on Air Force Air and Space operations. SEAS was developed to support acquisitions decisions of emerging capabilities early in the development life cycle, and is used to support the "exploratory analysis of new system concepts, system architectures, and Concepts of Operations (CONOPS) in the context of joint warfighting scenarios" (TeamSEAS 2017). SEAS seems to have some significant capabilities regarding simulating space, space capabilities, and space support activities to warfighters in a D3SOE, which is of direct interest to my work.

5. SCT (Space Capability Tool)

SCT is a model prototype that consolidates the functionality of many other Air Force models. It provides Air Force users with a "Google Earth-based tool that provides the impacts to Space and the Warfighter, as well as mitigating Tactics, Techniques and Procedures (TTPs) if Space capabilities are degraded or destroyed" (DOD M&S Catalog

2017f). It does not model ground combat operations well, but because of its classified nature, is capable of taking national level intelligence and capabilities to more accurately assess space impacts to Air Force operations.

6. SB (Space Brawler)

SB is a data package designed to supplement SEAS by providing the space community with a government owned “baseline, version control model of space operations that provides a standard point of departure, which can rapidly be modified or tailored for quick turn studies with a focus on space” (DOD M&S Catalog 2017e). SB significantly reduces the resource and time requirements necessary to develop a SEAS scenario by providing an operational foundation of steady-state space operations.

7. SIAM (Space and Information Analysis Model)

SIAM is an effects-based targeting support tool used to optimize collection and targeting priority of available weapon systems against adversary systems. SIAM can be used to “display communications paths, identifies choke points, prioritizes targets, assesses weapons planning, and identifies intelligence collection shortfalls” (DOD M&S Catalog 2017g). This is a useful tool for addressing the impacts from adversary counter-space threats and prioritizing them for targeting.

8. Guardian (GUARDIAN)

Guardian is a visualization tool used to assess when a specific space system may be vulnerable to adversary counter-space activities. It provides users a PC-based vulnerability analysis tool for the “visualization and analysis of space system susceptibility to counterspace threats” (DOD M&S Catalog 2017c), but it does not assess the impacts from these possible attacks. This is a planning tool, which is useful for anticipating periods when systems can be attacked based on threat capabilities.

9. JCATS (Joint Conflict and Tactical Simulation)

JCATS is an interactive (Virtual) M&S tool that is used by the Army to support training, analysis, and planning. JCATS is capable of simulating a wide range of OEs, as well as a wide range of mission sets and force structures. Because of its primary use as a

training tool, JCATS requires a significant amount of human input and resources to develop and execute scenarios.

10. AWARS (Advanced Warfighting Simulation)

AWARS is an Army comparative analysis tool designed to provide users a multi-sided, deterministic, DE simulation environment that can represent "land and amphibious warfare from brigade combat team (BCT) to division or JTF level" (DOD M&S Catalog 2017a). The Army uses AWARS for a wide range of activities to include concept exploration, experimentation, force structure analysis, as well as trade-space comparison.

11. JTLS (Joint Theater Level Simulation)

JTLS was designed to support the operational planning, training, and analysis requirements of joint planning staffs, specifically at higher level organizations like BDE and above. JTLS is an "interactive, multi-sided wargaming system that models a joint and coalition force air, land, and naval warfare environment" (DOD M&S Catalog 2017d), and thus, has little relevance to tactical and operational level organizations.

12. OneSAF (One Semi-Automated Forces)

OneSAF is a variable resolution M&S package originally designed to meet the training requirements faced by the Army during its recent transformation. OneSAF is an entity level model, specifically focused on supporting "constructive and virtual training, computer-generated forces, and mission rehearsal designed for brigade-and-below, combat, and non-combat operations" (U.S. Army 2013b, 264). While OneSAF was developed to supports the wide range of M&S tasks, to include constructive modeling, it was primarily designed to support virtual (human in the loop) training.

13. AFSIM (Adv. Framework for Simulation, Integration and Modeling)

AFSIM is an Air Force agent-based model designed to simulate the full range of joint operations from ground to space, at various levels of resolution, at the mission and below level. AFSIM consists of three components, which include a framework, an Integrated Development Environment (IDE), and a visualization tool, and provide users with "a flexible and easy to use agent modeling architecture which utilizes behavior trees and hierarchical tasking" (Clive et al. 2015, 73). AFSIM is a fairly complex model, and

although it has primarily been used to model space and air operations, should be capable of modeling ground operations in enough detail to make it useful. While it is ITARS restricted, and requires approval for use, it is available through request.

14. COMBATXXI (Combined Arms Analysis Tool for the 21st Century)

COMBATXXI is the premier Army combat model, and was developed to replace past M&S packages in order to meet current and future Army M&S needs. The goal was to design a more accurate high resolution entity level "analytical simulation tool used for weapon systems and tactics evaluation in brigade and below combined arms conflicts" (DOD M&S Catalog 2017b). By tying modeling responses to metrics of combat effectiveness, COMBATXXI greatly aids operational support to a high level of detail.

As it stands, a list of fourteen potential M&S packages was a fairly large group to investigate in any detail, so I thought it was best to start by screening out any M&S packages that would not meet my initial, hard line research needs. To do this effectively, I started by formally defining and documenting what "my needs" were in order develop a better understanding of the problem. By carefully outlining how I wanted the model to act, and what the intended purpose is, I was possible to significantly screen potential modeling platforms to a more manageable list for explorations.

C. INITIAL SCREENING

With the initial research complete, a matrix was created to examine how each of the fourteen potential M&S packages addressed the requirements as outlined in the OC. Some of these requirements were non-quantifiable, but based on my subjective assessment of each M&S package's ability to meet the requirements I attempted to be as inclusive as possible. Thus, I only screened out M&S packages that I was fairly certain could not meet my needs as outlined in the OC. The initial Screening Matrix can be seen in Table 67.

Table 67. Initial Screening Matrix

				DoD M&S Catalog										
Screening Matrix	NPS			AF Space					Army Training				AF	Army
Factors	MANA	JDAFS	OSM	SEAS	SCT	SB	SIAM	Guardian	JCATS	AWARS	JTLS	One SAF	AFSIM	COMBATXXI
Unclassified	Yes	Yes	Yes	Yes	No	ITAR	Yes	Conf	Yes	Yes	Yes	Yes	ITAR	Yes
Access/Availability of M&S	Yes	Yes	No	Request	Prototype	Request	Request	NIPR	Limited	Request	Request	Request	Request	Yes
Ground Force Opperations	Yes	Yes	No	Limited	No	Limited	No	No	Yes	Yes	Yes	Yes	Limited	Yes
Space Enabled	Limited	Limited	Limited	Yes	Yes	Yes	Limited	Yes	Limited	Limited	No	Limited	Yes	Limited
Stochastic Model	Yes	Yes	Yes	Yes	UNK	Yes	UNK	UNK	Both	No	Both	Yes	UNK	Yes
Constructive	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Both	No	Both	Yes	Yes

As shown in Table 67, of the fourteen potential M&S packages examined, seven (highlighted in red) failed to meet the baseline requirements for my research as outlined in the OC, and thus, would be excluded from further consideration. The most common reason for exclusion was the inability to adequately model ground combat operations. With my research focusing on capturing impacts to combat effectiveness of ground force in a D3SOE, I must have a combat model capable of adequately representing ground combat, to include appropriate response factors and MOEs. This screened out three Air Force M&S packages and one Navy M&S packages (OSM, SCT, SIAM, and Guardian).

Two more Army training M&S packages were also screened out because they were not constructive (JCATS and JTLS). While human-in-the-loop simulations are powerful training and analysis tools, they do not lend themselves to DOE where thousands of simulation runs would be needed to effectively evaluate COAs and competing design alternatives.

Finally, another Army training M&S package was screened for being deterministic (AWARS). While deterministic M&S packages have their place, I do not find deterministic models appropriate within the context of my research where the variability of combat will be intrinsically important to capture the effects of a D3SOE on combat effectiveness. A more detailed description of why each of these seven potential M&S packages was screened follows.

1. OSM

OSM is in early development, and is not capable of meeting many of my needs as outline in the OC without significant application of resources, namely in the complete development and integration of the ground component and communications architecture.

2. SCT

SCT is a Web-Based JWICS M&S package prototype, and while it has potential for follow on work in classified expansions to my work, its status as prototype and its classification rule it out for potential use. Additionally, because it is an Air Force model, the complete development of the ground component would be required.

3. SIAM

SIAM is a targeting tool used for prioritization, allocation, and assessment of weapons effects on targets. It is an optimization tool, not a simulation in the sense that behaviors can be monitored. There are no means in which to include ground combat forces into this model, and thus it fails to meet a primary requirement for my needs.

4. Guardian

Guardian is a vulnerability assessment tool for assessing space system susceptibility to known counter-space threats. It is a tool, not a simulation, and while it can be used for analysis, it has little use in tying space vulnerabilities and threats to impacts on combat operations, and no capability to model ground combat operations.

5. JCATS

JCATS is an interactive (non-constructive) training, analysis, and mission planning/rehearsal tool. It was designed to train large groups of people, not for use in large DOE experimentation. It requires extensive time and resources for employment, with numerous humans in the loop simulations running for days at a time. Thus, there is no way to generate the required amount of data needed to be useful in my work.

6. AWARS

Is a deterministic combat model with significant operational and performance input requirements used for studies and analysis. It is more geared toward training and planning than simulation, and its nature as a deterministic model make it unusable for my purposes, which rely heavily on modeling uncertainty in order to capture variability.

7. JCATS

Like JTLS, JCATS is an interactive (non-constructive) analysis tool for use in the development of OPLANS, and thus, for the same reasons as JCATS, is not suited for my purposes. After removing these seven M&S packages based on failure to meet requirements as outlined in my OC, seven potential M&S packages remained, which can be seen in Table 68.

Table 68. Remaining M&S Packages after 1st Screening

			DoD M&S Catalog				
Screening Matrix	NPS		AF Space		Training	AF	Army
Factors	MANA	JDAFS	SEAS	SB	One SAF	AFSIM	COMBATXX
Unclassified	Yes	Yes	Yes	ITAR	Yes	ITAR	Yes
Access/Availability of M&S	Yes	Yes	Request	Request	Request	Request	Yes
Ground Force Opperations	Yes	Yes	Limited	Limited	Yes	Limited	Yes
Space Enabled	Limited	Limited	Yes	Yes	Limited	Yes	Limited
Stochastic Model	Yes	Yes	Yes	Yes	Yes	UNK	Yes
Constructive	Yes	Yes	Yes	Yes	Both	Yes	Yes

D. SECONDARY SCREENING

Once I had screened the list of potential M&S platforms based on the questions asked in developing the OC, I was then able to do additional screening based on other additional, “secondary” factors that while not critical to the success of an M&S Packages ability to meet my primary needs, can have an impact on my ability to efficiently conduct my research. These secondary screening considerations focus on aspects like usability, ease of use, and resource requirements to name just a few.

While individually these will likely not screen any M&S packages from consideration, if any M&S package fails to meet a significant number of these secondary considerations it is justifiable to screen them from further consideration. While this is a subjective assessment, due to the fact that I am the one conducting the research I believe that it is acceptable. With this in mind, and because the purpose of this dissertation is to provide a proof of concept and to develop and describe the methods and tools required to meet my research objectives, I was able to highlight some secondary screening

considerations with regards to any potential M&S packages by addressing the following usability considerations.

1. Are there existing models?

It is advantageous to use an existing model and modify it to my purposes rather than to develop my own from scratch. Starting from an established model will greatly reduce the amount of effort and time required to develop the highly detailed model needed for my research.

2. Is there access to the M&S package and additional resources?

It is advantageous to use an M&S package that is freely available, with a detailed manual and resident expertise and support here at NPS. Using an M&S package that is highly used at NPS would increase the availability of resources and support which could greatly reduce the time and effort of model development, data production, and analysis.

3. How usable is the M&S package?

It is advantageous to use an M&S package that is easy to use, has a quick learning curve, is capable of rapid development and iterative modification, as well as having a relatively low level of complexity. Because my work would require significant development and T&E to reach face validation of the operational model, an M&S package that could be rapidly modified and run repetitively without the use of external IDEs or packages was advantageous because it would greatly decrease the complexity of the overall process.

4. Can it model ESINQ effects?

It is advantageous to use an M&S package that has the capability to model directly or through indirect representation the impacts of a D3SOE on combat effectiveness. Having an M&S package that already had the “knobs” to turn to represent the effects of counter-space activities would be greatly reduce the development time needed to represent these effects in the combat model.

5. Does it support large scale DOE at NPS?

It is advantageous to use an M&S package that is capable of being executed following a specified DOE on the NPS computer supper cluster. Any M&S package that has already had execution scripts developed for use with the cluster would be of further use. This would allow for the execution of a large number of simulation runs without a significant amount of resources to build the required scripting language to execute the M&S package according to a DOE on the computer cluster, which will drastically decrease the time required to produce output data, and allow for more routine use of the cluster which will increase the development tempo.

Taking these five considerations into account and applying them to the initial screening matrix seen in Table 68, it was now possible to conduct a secondary screening of the remaining potential M&S packages based on the additional considerations in order to further reduce the number of potential M&S packages. Table 69 shows the status of the remaining candidate M&S packages following this secondary screening.

Table 69. Potential M&S Packages Following Secondary Screening

			DoD M&S Catalog				
Screening Matrix	NPS		AF Space		Training	AF	Army
Factors	MANA	JDAFS	SEAS	SB	One SAF	AFSIM	OMBATXX
Unclassified	Yes	Yes	Yes	ITAR	Yes	ITAR	Yes
Access/Availability of M&S	Yes	Yes	Request	Request	Request	Request	Yes
Ground Force Opperations	Yes	Yes	Limited	Limited	Yes	Limited	Yes
Space Enabled	Limited	Limited	Yes	Yes	Limited	Yes	Limited
Stochastic Model	Yes	Yes	Yes	Yes	Yes	UNK	Yes
Constructive	Yes	Yes	Yes	Yes	Both	Yes	Yes
Level of Resolution	Low	Low	Variable	Variable	Variable	High	High
Complexity	Low	Mod	High	Mod	High	High	High
Updated Model (current)	Yes	Dev	Yes	Yes	Yes	Yes	Yes
Mission level	Mission	Mission	Variable	Variable	Variable	ngagmen	Mission

As shown in Table 69, of the seven remaining M&S packages, four (highlighted in Dark Orange) were identified for screening due to a combination of factors that contributed to a high level of uncertainty regarding the amount of effort needed to use them in support of my work. Three failed to meet the secondary considerations for this

research, which screened out one Air Force and two Army M&S packages (AFSIM, OneSAF, and COMBATXXI). Thus, these would be excluded from further consideration as potential M&S packages. The primary reason for exclusion was the relatively high resolution and complexity of the models. With my research focusing on providing a proof of concept, an overly high resolution model would likely induce unneeded complexity. While having a combat model capable of adequately representing ground combat is needed, it does not need be overly complex or detailed as long as the effects are accurately represented. Thus, high resolution models, while more accurate, are not necessarily needed for this work. If my work is successful, future expansion of this work can include the use of higher resolution and higher complexity models. A more detailed description of why each was screened out follows.

1. AFSIM

AFSIM is currently used within some Air Force communities as an Air combat model, and while it is a fairly powerful M&S package, it does not treat ground combat equally. Thus, there would be a significant learning curve and long development time to implement any ground combat scenario, and the accuracy and functionality of this model would be questionable. AFSIM is an detailed and highly complex space model that utilizes a fairly low resolution representation of ground combat. The combination of these factors induces too much uncertainty to seriously consider it as a potential M&S package for my research.

2. OneSAF

While OneSAF is heavily used by the Army, it was primarily developed as a tool to support virtual training. While it has capabilities to support constructive modeling, it was not built with that as the primary purpose. Thus, use as a constructive tool still requires a significant amount of manpower and resources compared to other purely constructive M&S tools. Thus, it would not be considered further.

3. COMBATXXI

COMBATXXI is likely the best combat model which I investigated, and easily has the most capability of any of the M&S packages I investigated to model ground

combat, with the potential for modeling a D3SOE. Unfortunately, it was by far the most complex of all of the models I investigated, with a high level of detail. While I will recommend the Army use it during the future expansion of this work, its high level of complexity and detail are simply overkill with regard to this dissertation.

This left four potential M&S Packages as seen in Table 69. While these four met both my initial and secondary screening requirements, one key issue needed to be addressed before moving forward. This issue revolved around the fact that SB is not an M&S package, but rather a data package for implementation within SEAS. This package provides a complete simulation foundation of steady state operations for SEAS model developers to start from in order to significantly reduce the complexity of the development phase. Thus, some additional screening consideration was needed.

One final screening consolidation was done to take advantage of the linkages between SEAS and SB. SEAS is a simulation framework, and by itself, would require a significant development effort to achieve a usable model for my dissertation. While a powerful tool that is likely fully capable of meeting my needs, when considering the limited resources available to me, the feasible of using SEAS as my M&S package comes into question. Enter Space Brawler. Thus, if SEAS is used with SB, it would likely provide enough of a foundational starting point to make the use of the SEAS package feasible. Therefore, the combination of the two will be included it in the detailed screening. Table 70 shows the remaining three M&S packages that I will be considering in the detailed exploration.

Table 70. Final M&S Packages

			DoD M&S
Screening Matrix	NPS		AF Space
Factors	MANA	JDAFS	SEAS/SB
Unclassified	Yes	Yes	ITAR
Access/Availability of M&S	Yes	Yes	Request
Ground Force Opperations	Yes	Yes	Limited
Space Enabled	Limited	Limited	Yes
Stochastic Model	Yes	Yes	Yes
Constructive	Yes	Yes	Yes
Level of Resolution	Low	Low	Variable
Complexity	Low	Mod	Mod
Updated Model (current)	Yes	Dev	Yes
Mission level	Mission	Mission	Variable

As shown in Table 70, I have selected three potential M&S packages for further in depth investigation for utility as potential tools for use in my dissertation. While the selection of these potential M&S packages may draw some scrutiny, understand that the purpose of this dissertation is to define a methodology and develop decision support tools for the operational planning and acquisitions resourcing of emerging space systems through effectiveness based decision making. Thus, the method and tools, while not as accurate as can be, will meet the intent of this dissertation. If successful, it is my hope that the Army Space Operations, R&D, and Acquisitions communities sees the value that these methods and tools have, and will invest resources to expand the depth and breadth of my work, and creating a more robust methodology and tool set. This could include the use of better and more detailed models (COMBATXXI), VV&A M&S packages, classified information, higher levels of resolution, longer/larger combat scenarios, as well as using numerous different combat scenarios to produce a more robust outcome.

The following sections will explore in more detail the three selected M&S packages identified in Table 70. Each section will be devoted to a single M&S Package, and will cover: my initial observations; how the M&S package accounts for communication, GPS, and ISR degradation; potential input factors for representing a D3SOE; potential responses for combat effectiveness; model development; data output; DOE; analysis; and finally, my overall findings. The intend of this investigation is to

gather a much more detailed understanding of each M&S package's capabilities to support my research, and once compete, to weight each against each other in order to select the best M&S package for my use.

E. MODEL EXPLORATION

1. Exploration of MANA

MANA was one of the first combat models I was exposed to, and there is a wealth of resident experience and knowledge at NPS that greatly aided in my investigation. MANA was designed to allow users to explore a wide range of scenarios at a relatively low resolution, and was developed around two key ideas: First, "that the behaviour of the entities within a combat model (both friend and foe) is a critical component of the analysis of the possible outcomes. [Second], that we are wasting our time with highly detailed physics-based models for determining force mixes and combat effectiveness" (McIntosh et al. 2007, 2). Having interest in modeling combat, especially how agent personalities can impact combat effectiveness, this statement peaked my curiosity. When combined with the fact that one of MANAs goals is to support the modeling of communications and the sharing of SA, which is essential for implementing and degrading space dependencies, led me to conclude that MANA may be a appropriate M&S tool for modeling combat operations in a D3SOE.

a. Initial Observations

My initial investigation of MANA was focused on getting a feel for the usability of the model, how it operated, and how easily it could be developed and modified. Additionally, I wanted to investigate the factors within the model that could be modified to "represent" the potential impacts from operations in a D3SOE. When it comes to usability, MANA is extremely user friendly, with a relatively quick learning curve. It comes with a pretty detailed user manual, and there are numerous experts available locally to support model development and troubleshooting. MANA has been extensively used in research at NPS, especially in the OR department where it has been used as the primary M&S package for more than twenty thesis and at least three dissertations. Thus, there are ample model available from which I can use to build my work.

My initial investigation included a look at the factors in MANA that I thought I could use to model the impacts from a D3SOE. I did this by manipulating various factors individually to develop a better understanding of how the model used these factors. What I discovered, as I expected, is that there is no direct/specific factor settings for degrading communications, ISR, and GPS. Luckily, there seem to be ample ways to "represent" the expected impacts and effects of a D3SOE through the modification of other existing factors within MANA and using these factors as "surrogates" for the expected impact. The following MANA input factors were identified as potential surrogate factors for which modification could represent impacts from counter-space activities in a D3SOE.

b. Potential Input Factors for Representing a D3SOE

A major focus of my work is in the modeling of combat operations within a D3SOE. Broadly speaking, the effects of a D3SOE on combat operations can be binned into three distinct groups. The first is communications degradation, when an adversary's use of counter-space capabilities restricts the flow of friendly information. Second is ISR degradation, when an adversary's use of counter-space capabilities restricts a friendly forces' ability to collect information. The third is PNT degradation, when an adversary's use of counter-space capabilities degrades the accuracy and availability of critical position and timing signals of friendly forces. During my brief investigation of MANA I inspected agent attributes and factor settings that I believed could potentially be modify and used as a method for representing the effects of a D3SOE with respect to communications, ISR, and PNT degradation.

Communications Degradation

Here, from the development of MANA, there are several potential factors which we can use to degrade communications. Since each agent shares information with others through communications links, it is easy to build accurate communications links to represent real world communications. These links could then later be degraded to various levels based on the expected impacts from adversary jamming. Factors which I identified as being likely surrogates for representing these effects were: Inter-Squad Comms

Accuracy, Inter-Squad Comms Latency, Inter-Squad Comms Reliability, Inter-Squad Comms Capacity, and Intra-Squad Comms Delay, which I will now define.

- Latency

The MANA manual describes latency as the "number of time steps taken for each message to reach the receiving squad" (McIntosh et al. 2007, 70). Latency was a fairly significant factor and seems to be a good factor for representing impacts to communications and SA. Care will need to be taken when using latency to accurately depict communications and the passing of SA because MANA assumes instantaneous dissemination of SA throughout the squad after it is successfully communicated. Thus, delays in incorporation of the SA throughout the squad will need to be added to the overall latency if desired.

- Reliability

The MANA manual describes reliability as "the likelihood that a given message will be successfully sent on the link per attempt" (McIntosh et al. 2007, 70). Reliability was also a somewhat significant factor and seems to be a moderately useful factor for partially representing the impacts to communications and SA error. While its overall impact was minimal, it was enough to keep for further investigation. Reliability intuitively makes sense and is easy to explain, but care will need to be taken when determining its impact; it will likely have significant higher-order interactions.

- Intra-Squa**d** Comms Delay

The MANA manual states that comms delay "specifies the number of time steps that must pass before an agent's contact information is placed onto its parent squad SA map" (McIntosh et al. 2007, 66). Intra-Squad Comms Delay was a fairly significant factor but will likely be a poor factor for use to represent impacts to communications and SA. Like reliability, it intuitively makes sense and is easy to explain, but when considering the fact that most combat squads have line of sight communications with each other, it is hard to justify that these types of communications could be degraded by adversary actions. Thus, while delay will likely be something other than zero, it will likely be constant, and therefore will not be included in my detailed investigation.

- Accuracy

The MANA manual describes Accuracy as the "probability that a contact's type will be passed correctly….an accuracy of 0% results in always sending an incorrect contact type while 100% means the information will always be sent as correct contact type" (McIntosh et al. 2007, 70). While accuracy was a significant factor it should not be used to model locational or positional error. Because MANA models accuracy as an "error of classification," and not a positional error, it is not a good factor for my purpose, it is misleading. Though it has some use as an uncertainty factor to induce fratricide, I found that modifying it much below 95% induces large numbers of agent state changes, from enemy to friendly and back again. Thus, I will not use this as an input factor.

- Capacity

The MANA manual describes capacity as the "number of messages that can be sent through the link per time step" (McIntosh et al. 2007, 70). Capacity was the least significant factor and is a poor factor for representing the impacts to communications from a D3SOE. Because MANA models communications links individually, with no common links, this factor serves to only limit the number of messages per time step, per link. If 10 contacts are made in a time step, and there are four outbound links, a capacity of 10 for each link would be needed to complete the update for that time step. But this is not how HQs disseminate SA to subordinates, which is done over a single digital link simultaneously. Thus, capacity does not accurately represent actual communications, and it will not be considered in further investigations.

ISR Collection Degradation

Here I took advantage of the fact that for Intel to reach the forces that need it, it must travel through a communications network. Thus, I can degrade the info link piece in conjunction with the communications degradation in the exact same manner as done previously. To induce impacts from the loss of ISR capabilities itself, I can do this in two ways. First, for systems with representative agents in the model such as UAVs, HAASs, and SmallSats, it is possible for the adversary to kill them, and thus the degradation of the system will be induced into the model directly. Second, for systems that do not have an

agent representing it directly, such as higher HQ SIGINT, ISR, and other higher echelon UAVs, I can simply create a separate sensor at the HQ element that can observe the entire battle space to represent each of these intel sources. Then, by manipulating the sensors probability of detection or time between detections, I can represent various degrees of degradation of the specific collection asset. Thus, factors which I identified as being likely surrogates for representing these effects were probability of detection and time between detections.

- Detection Range-Time Table

The MANA manual describes detection range as "the average amount of time between detection events for ranges *r* less than or equal to the specified range *R* (and greater than the next lowest range, if specified)" (McIntosh et al. 2007, 58). Detection range was a fairly significant factor and seems to be a good factor for use to partially model the impacts from degraded ISR collection capabilities or the loss of these systems. This factor becomes increasingly important the more dependent operations are on higher UAV, ISR, and SIGINT collection capabilities. Since this intelligence directly impacts the success of higher HQ and local fire support, I expect a significant impact to operations as intelligence collection is degraded. Therefore, I believe that this will be a fairly significant factor, so I will keep it for further investigations.

- Classification Range-Probability Table

The MANA manual describes classification range as "the probability of acquiring a target for classification purposes once it has been detected on a given time step for ranges of less than or equal to the specified range (and greater than the next lowest range if specified)" (McIntosh et al. 2007, 58). Like detection range, classification range was a fairly significant factor and seems to be a good factor for use to partially model the impacts of degraded ISR collection capabilities. But these impacts can also be represented in the average time between detections, and rather than manipulating two factors to represent the same effect, I decided to keep this factor constant and modify the average time between detection. Thus, this factor will no longer be considered.

PNT Degradation

Here, there was no direct correlation to any factors that could induce the type of degradation I was looking for. MANA does not have a method to induce positional error or represent location uncertainty by agents. Once an agent is detected and classified, its location is known without error. Additionally, all agents always know exactly where they are. In reality this is never the case, and in a D3SOE it is even further from the truth. Unfortunately, agents have perfect SA, at least for what they have detected or have been told about. So the question is how can we trick the model into demonstrating behaviors that can mimic locational inaccuracies? This must be considered in a few different ways. First, for movement, one must understand that most ground forces have redundant maps and compasses that they can use in conjunction with terrain recognition to navigate. Thus, while not optimal, and likely slowing the decision making process and pace of battle, ground forces can still maneuver. So it is easy to argue that the maneuver speed of these forces, which is a factor we can manipulate as a surrogate, will be slower, at least while not in contact. Secondly, for fires, the only fires that are affected by GPS inaccuracies are indirect fires like artillery and deep strike capabilities. All direct fire forces can physically see their adversaries, and are not affected by locational errors at all. Thus, for the indirect fire systems, likely surrogate factors that we can use to represent locational and targeting inaccuracies include the munitions P_h, the blast radius, or the number of hits to kill of the target.

- Movement Speed

The MANA manual describes movement speed as "the number of cells an agent can move in a given time step" (McIntosh et al. 2007, 51). Movement speed was a significant factor and seems to be a moderately appropriate factor for use for partially representing the impacts from location and positional error. Positional error would likely induce uncertainty, and thus slow the speed of movement as decision makers are forced to collect more information to account for the increased uncertainty. Care will need to be taken when determining the impacts and should be done by squad by mission, based on proximity to targets. Ground forces should be the least impacted, while artillery, who are

semi-dependent on position and target accuracy should be more impacted, and deep strike, precision weapons systems, aviation, and UASs should be the most impacted.

- Range/Hit Rate per Discharge

The MANA manual describes hit rate per discharge as "the hit rate per firing of the weapon for specified ranges" (McIntosh et al. 2007, 62). Hit rate per discharge was a fairly significant factor and seems to be a good factor for partially representing the impacts from degraded targeting information for indirect fires. Hit rate per discharge becomes increasingly important as operations become more dependent on higher level fire support. As more and more preparatory and support fires are utilized, the bigger the impact will be in a D3SOE. Therefore, I think this is a fairly significant factor and will likely have several higher-order interactions, so I will keep it for further investigation.

In conclusion, based on this analysis, the following surrogate input factors (from this point forward referred to simply as factors) will be used in my analysis. First, for communications degradation, I have chosen to ignore accuracy, intra-squad delay, and capacity. I will use a combination of latency and reliability to represent communications degradation for all links. Next, for ISR collection degradation, I have chosen to ignore classification range. I will use average time between detections (detection range) to represent the impacts of degraded ISR collection on collection assets. Finally, for PNT degradation, I choose to keep both factors. I will use movement speed to represent degradation of positional and destination accuracy for all moving agents, as well as hit rate per discharge to represent the impact of degraded targeting data for all indirect fire agents. The combination of these five input factors should give me adequate capacity to represent the effects and impacts from a D3SOE on combat operations.

c. Potential Output Responses for Combat Effectiveness

With potential input factors identified, it is now time to investigate the available output responses MANA provides in order to determine its feasibility for use in my research. Because MANA is a combat model, its outputs naturally include a host of relevant combat statistics to include force losses, losses by source, as well as killer-shooter information. Thus, it is easy to generate measures of combat effectiveness for

comparison, such as FER, LER, and LoB to name just a few. Because this is a exploration, I will be looking at several potential output responses in order to investigate their potential for accurate representation of combat effectiveness. Thus, it seems MANA is well equipped to provide adequate output data needed to enable a large scale DOE and drive meta-model development.

d. Model Development

For this exploration, I started with a toy model provided by Prof Jeff Appleget in his Combat Modeling Course. I then expanded it to include specific agents from the works of Treml (2013) and Soh (2013), specifically the Mechanized Infantry and Attack Aviation from Treml and the UAVs from Soh. I then significantly expanded the model, agent behaviors, capabilities, and other factors to loosely represent a potential scenario based on my understanding of the new AOC. Through trial and error over the course of a month, I completed over 20000 development simulation runs until I reached a point where I believed the agents in the model were mostly acting as expected, and the output was about what I would expect. This face validation would be sufficient for this initial investigation, and yielded a force-on-force combat simulation where the Blue forces are attacking a Red force.

Red forces are fighting from well prepared positions, are comparably equipped and trained, and are on their own home turf. The Blue force was comprised of a Battalion (+), comprised of Armor, Mechanized Infantry, Anti-Tank, Infantry, Artillery, Aviation, and fires/intel support from higher, for a total of 140 agents. The Red forces were comprised of a similar mix of forces minus the aviation, Mechanized Infantry, and UAV assets, with the addition of Air Defense Artillery (ADA) assets, for a total of 52 agents. Therefore, the Blue force enjoys roughly a 3–1 military advantage. Thus, roughly speaking, with all things equal, even though Blue forces do have a better and more capable force structure, we should expect the Blue force to win about 50% of the time. Figure 100 describes the starting positions for the simulation.

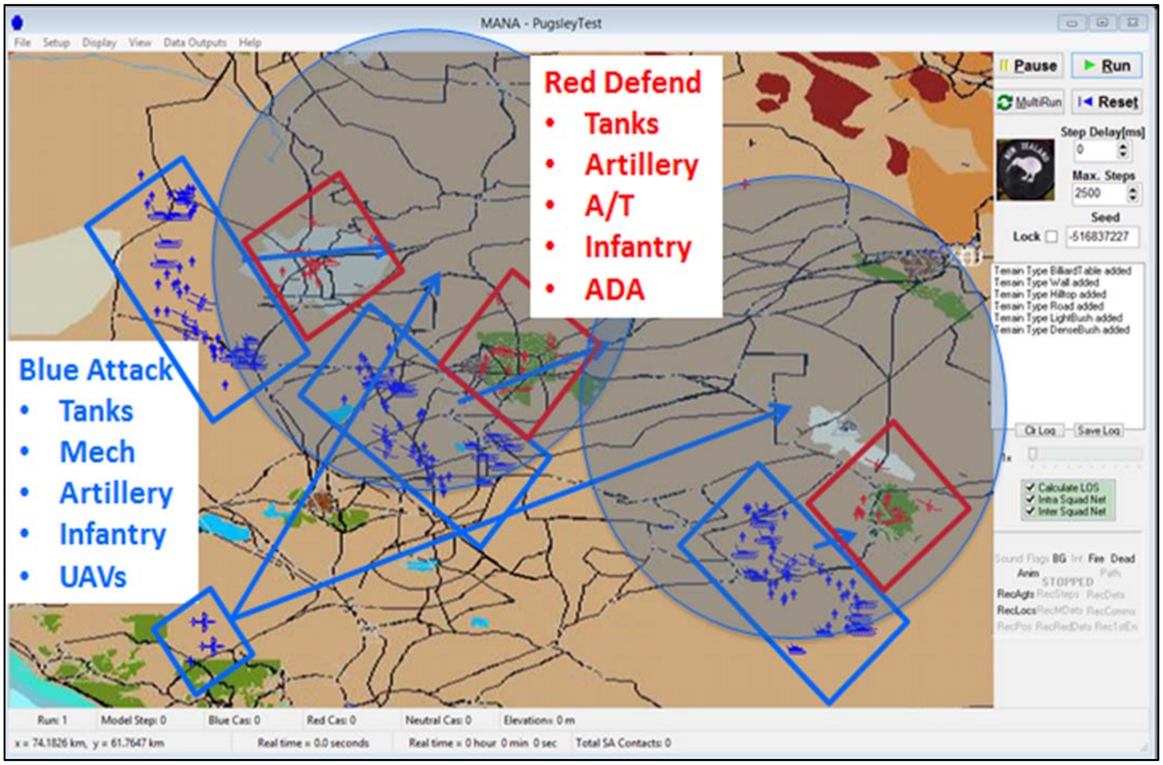


Figure 100. MANA Screenshot

For the victory/stop conditions, I choose to establish the following break points where either side would withdraw from the fight, and thus end the simulation. For the defending Red forces, I determined that they would fight to a break point of 40 casualties, or after the loss of roughly 75% of their starting strength. For the Blue forces, I set the break point to 70 casualties, or after the loss of roughly 50% of their starting strength. Additionally, I set a maximum run length of 2500 time steps (3.5 hrs.), this would call a tie if victory was not achieved by either side. I did this to limit situations where the neither side could reach victory.

e. DOE

Now that the exploration and development of the model was complete, it was time to perform a DOE to produce output in which I could conduct analysis and develop models to represent the impacts of varying factors on their impact to the combat effectiveness of the blue force. Table 71 shows the five selected design factors which will

be used as surrogates for representing the effects of a D3SOE on combat operations. These include Latency, Reliability, Movement Speed, Hit Rate per Discharge, and Time between Detections, and included the high and low values for each factor in the design.

Table 71. DOE Design Factors and Levels

Factors	Name	Squad	Location	Tab/Link	Setting	Low Value	High Value	# Decimiles	Base Case
1	B Inf Latency	1	Inter Sqd SA	All Links	Latency	2	24	0	2
2	B Tank Latency	3	Inter Sqd SA	All Links	Latency	2	24	0	2
3	B Arty Latency	4	Inter Sqd SA	All Links	Latency	2	24	0	2,4
4	B AT Latency	5	Inter Sqd SA	All Links	Latency	2	24	0	2
5	B HQ Latency	9	Inter Sqd SA	All Links	Latency	2	48	0	12
6	B UAV Latency	11	Inter Sqd SA	All Links	Latency	2	48	0	30
7	B Helo Latency	13	Inter Sqd SA	All Links	Latency	2	24	0	2
8	B Brad Latency	14,16,18,20,22,24	Inter Sqd SA	All Links	Latency	2	24	0	2,4
9	B Brad Inf Latency	15,17,19,21,23,25	Inter Sqd SA	All Links	Latency	2	24	0	2
10	B Inf Reliability	1	Inter Sqd SA	All Links	Reliability	50	100	2	95
11	B Tank Reliability	3	Inter Sqd SA	All Links	Reliability	50	100	2	95
12	B Arty Reliability	4	Inter Sqd SA	All Links	Reliability	50	100	2	95
13	B AT Reliability	5	Inter Sqd SA	All Links	Reliability	50	100	2	95
14	B HQ Reliability	9	Inter Sqd SA	All Links	Reliability	50	100	2	95
15	B UAV Reliability	11	Inter Sqd SA	All Links	Reliability	50	100	2	95
16	B Helo Reliability	13	Inter Sqd SA	All Links	Reliability	50	100	2	95
17	B Brad Reliability	14,16,18,20,22,24	Inter Sqd SA	All Links	Reliability	50	100	2	95
18	B Brad Inf Reliability	15,17,19,21,23,25	Inter Sqd SA	All Links	Reliability	50	100	2	95
19	B Tank Default Speed	3	Tangilbles	Default State	Movement Speed	7	15	2	15
20	B Arty Default Speed	4	Tangilbles	Default State	Movement Speed	5	10	2	10
21	B AT Default Speed	5	Tangilbles	Default State	Movement Speed	6	13	2	13
22	B Helo Default Speed	13	Tangilbles	Default State	Movement Speed	45	90	2	90
23	B Bradly Default Speed	14,16,18,20,22,24	Tangilbles	Default State	Movement Speed	7	15	2	15
24	B HQ Higher Deep Strike	9	Weapons	1	Hit Rate per Discharge	0	0.8	2	0.8
25	B Arty Prob of Hit	4	Weapons	1	Hit Rate per Discharge	0.2	0.8	2	0.8
26	B UAV Sensor ISR Vehicle	11	Sensors	1	Detect: Ave Time Between Detections	2	600	0	2
27	B Arty Radar	4	Sensors	3	Detect: Ave Time Between Detections	10	240	0	10
28	B HQ Sensor ISR	9	Sensors	2	Detect: Ave Time Between Detections	150	1800	0	150
29	B HQ Sensor Sigint	9	Sensors	1	Detect: Ave Time Between Detections	120	1800	0	120

As shown in Table 71, when multiplying the five input factors across the number of agent squads these factors impacted, left me with a 29 factors design that would attempt to represent the impacts from combat operation in a D3SOE. Because I had no *a priori* regarding the model, I was interested in maximizing to the greatest extent possible the insight I could gain from this investigation. With no expectations for the output, which factors were significant, nor the level/orders of interactions (1st order, 2nd order, higher-order interactions, I decided that a NOLH design would give me the most ability to explore the tradespace and still be able to identify non-linearity and higher order interactions. With that said, the 257 DP design shown in Table 72 was created using the NOLHdesigns_v5.xls tool, which is available on the HARVEST website at https://harvest.nps.edu.

Table 72. NOLH Design Matrix.
Source Naval Postgraduate School (2017).

low level	2	2	2	2	2	2	2	2	2
high level	24	24	24	24	48	48	24	24	24
decimals	0	0	0	0	0	0	0	0	0
actor name	B Inf Latency	B Tank Latency	B Arty Latency	B AT Latency	B HQ Latency	B UAV Latency	B Helo Latency	B Brad Latency	B Brad Inf Latency
	11	21	15	15	31	43	24	21	6
	5	11	20	23	35	26	23	21	14
	6	15	5	14	46	39	23	22	16
	11	6	11	16	36	36	21	23	5
	10	14	15	11	45	38	19	17	3
	12	10	23	6	42	44	18	23	18
	3	15	12	5	26	26	19	15	17
	11	3	10	11	45	36	17	17	13
	4	13	22	16	20	38	18	24	6
	13	4	21	18	4	30	14	14	23
	5	22	13	23	22	25	23	15	22
	4	5	4	18	19	33	19	16	13
	8	23	16	4	21	39	16	17	10
	3	8	18	5	9	39	24	13	18
	8	16	3	13	7	26	19	14	18
	10	8	8	4	20	35	23	21	4
	8	14	20	19	43	19	16	17	5
	12	8	20	15	26	15	21	17	19
	6	20	12	13	39	4	21	19	17
	6	6	8	17	36	14	19	22	12
	9	13	19	6	38	5	24	23	10
	13	9	15	6	44	8	21	20	19
	11	19	13	12	26	24	19	18	17
	7	11	9	8	36	5	20	16	12
	8	13	19	22	12	20	14	24	4
	13	8	22	14	20	4	17	22	19
	4	19	13	20	25	22	15	20	18
	7	4	8	18	17	19	17	14	12
	8	20	22	7	11	21	20	19	13

low level	50	50	50	50	50	50	50	50	50
high level	100	100	100	100	100	100	100	100	100
decimals	2	2	2	2	2	2	2	2	2
actor name	B Inf Reliability	B Tank Reliability	B Arty Reliability	B AT Reliability	B HQ Reliability	B UAV Reliability	B Helo Reliability	B Brad Reliability	B Brad Inf Reliability
	53.32	61.91	69.34	53.13	59.18	66.99	69.73	72.27	52.93
	80.47	81.25	87.11	100	94.34	75.59	51.17	53.13	56.84
	68.16	60.16	62.3	56.45	57.23	96.88	91.6	78.32	96.48
	77.34	96.88	89.06	98.24	97.66	82.23	79.1	89.45	100
	90.82	54.3	52.73	66.02	53.91	75.2	58.01	57.42	55.66
	72.85	91.99	88.09	91.99	85.35	95.7	71.29	69.14	72.07
	79.3	50.2	63.48	65.43	66.02	57.23	95.51	95.7	83.01
	53.52	73.24	76.56	90.43	82.62	71.29	95.31	86.52	91.6
	69.14	97.27	61.52	72.85	71.48	59.18	82.81	70.31	64.84
	87.5	70.12	84.18	87.89	97.46	56.64	77.93	72.07	55.47
	64.26	82.23	60.55	60.55	70.12	82.42	55.08	88.48	75.98
	99.41	71.88	74.61	99.02	81.84	85.94	71.68	79.88	90.04
	96.88	88.28	60.35	52.15	73.63	90.63	83.4	62.89	53.91
	58.98	67.58	88.87	83.59	83.01	80.08	93.36	71.09	67.19
	98.63	78.32	63.28	52.34	57.42	55.47	65.23	91.99	97.85
	75.2	50.59	76.37	88.67	78.91	58.79	68.36	85.35	86.52
	68.36	75.39	82.62	56.05	66.41	66.6	66.8	91.41	57.62
	89.26	95.31	62.11	80.47	81.45	73.83	58.59	94.34	59.18
	61.52	62.11	86.13	57.81	54.88	84.57	76.37	69.34	88.28
	71.68	90.23	50.98	92.77	90.43	88.67	92.38	64.26	85.55
	87.11	51.37	89.84	55.47	58.4	96.29	64.84	95.9	54.49
	55.86	87.11	52.15	97.46	99.22	74.22	63.67	70.9	62.11
	86.91	60.94	94.73	58.59	67.77	64.84	99.22	55.08	93.95
	69.34	74.22	75.2	86.72	87.11	62.7	83.98	50	98.63
	74.41	81.05	91.6	64.65	52.73	70.51	88.28	88.28	66.02
	95.12	60.74	62.7	74.22	98.05	65.04	75.59	75.78	69.73
	62.11	83.59	77.54	64.45	72.85	77.73	71.09	56.45	87.7
	90.23	76.17	71.09	78.32	90.23	99.02	62.11	65.23	78.13
	98.83	87.5	88.67	61.52	68.95	92.38	90.23	76.76	76.37

low level	7	5	6	45	7	0	0.2	2	10	150	120
high level	15	10	13	90	15	0.8	0.8	600	240	1800	1800
decimals	2	2	2	2	2	2	2	0	0	0	0
actor name	B Tank Default Speed	B Arty Default Speed	B AT Default Speed	B Helo Default Speed	B Bradly Default Speed	B HQ Higher Pr of hit	B Arty Prob of Hit	B UAV Sensor ISR Vehicle	B Arty Radar	B HQ Sensor ISR	B HQ Sensor Sigint
	7.28	5.86	7.94	55.9	9.34	0.3	0.31	32	78	543	166
	7.03	6.76	10.05	55.72	10.31	0.42	0.35	238	67	563	783
	13.75	6.21	6.57	51.86	7.28	0.25	0.21	259	77	878	435
	13.22	5.08	6.98	54.49	10.56	0.19	0.44	243	57	466	520
	9.22	9.65	10.59	82.97	13.88	0.23	0.4	142	74	1110	218
	9.97	9.45	12.1	85.78	14.84	0.46	0.22	240	50	724	350
	14.84	8.98	9.42	88.24	13.53	0.24	0.44	257	73	388	547
	11.91	8.4	11.93	88.07	14.38	0.18	0.36	72	108	272	330
	9.72	8.09	7.31	48.16	8.81	0.69	0.74	355	49	749	251
	9.03	9.12	9.47	57.3	10.34	0.41	0.66	292	64	627	212
	11.22	9.36	9.01	45.53	11.19	0.78	0.64	542	21	318	829
	13.69	8.07	7.83	59.06	9.25	0.63	0.65	394	63	156	868
	8.63	7.19	10.92	82.79	12.28	0.54	0.73	483	46	208	665
	9.47	7.21	9.61	88.59	11.91	0.69	0.77	572	22	717	310
	11.34	5.61	11.88	69.43	11.53	0.36	0.74	465	39	453	173
	11.47	7.36	11.5	74.36	14.28	0.66	0.8	586	92	820	855
	7.88	6.58	11.99	50.45	10.25	0.51	0.54	67	216	1748	973
	8.22	7.42	10.16	58.54	9.5	0.77	0.39	14	167	1162	1124
	12.91	5.06	12.62	49.57	8.44	0.75	0.33	285	226	1078	317
	11.53	5.94	12.73	49.75	7.22	0.53	0.28	156	169	1252	881
	10.28	8.93	7.04	76.11	14.47	0.5	0.42	271	159	1342	1104
	8.97	8.63	6.55	89.3	12.97	0.47	0.43	149	197	1516	402
	13.84	7.29	7.91	81.74	12.81	0.74	0.37	2	126	1059	875
	14.5	9.02	8.43	75.41	12.16	0.43	0.48	25	174	1800	586
	10.75	9	9.55	64.34	7.94	0.12	0.78	411	205	1085	474
	8.03	7.17	12.13	65.92	7.31	0.43	0.65	401	178	1136	894
	14.38	8.54	12.67	57.83	10.63	0.14	0.71	516	174	1665	652
	14.28	8.96	10.07	51.68	8.34	0.04	0.76	591	239	1065	179
	7.59	6.31	9.12	76.82	12.41	0.21	0.66	488	206	1658	199

Running each design point 1000 times for statistical significance led to the need for a simulation run of 25700 iterations of the model, to include an additional 1000 runs of the base case scenario. The replications were done using the NPS OR departments computing cluster, and was completed in less than a day. The availability and rapid turnaround of the MANA compatible computer cluster is a significant advantage of MANA as an M&S package. Since MANA is used extensively in the OR department, there resides a host of support for the M&S package, to include pre-existing scripting to enable rapid model execution of large scale designs. Because of the ability to rapidly develop and execute a large scale DOE, it is easy to produce enough output data for detailed analysis.

f. Analysis

The purpose of this analysis is to investigate the feasibility of MANA as a potential M&S for my dissertation. Thus, I will not be focused on analysis per say, but more on "how well" MANA supports my research needs for analysis. I am trying to determine the feasibility and potential of MANA to support the analysis needed to achieve my research outcomes as outlined in Chapter I. In order to test this, the following analysis uses the same general procedures as I expect to follow for my final research model, to include a broad case investigation as well as a more detailed NOLH analysis.

Base Case (1000 runs)

For my analysis of the base case scenario, I focused on developing an understanding of how the model functioned in a non-degraded scenario, i.e., a scenario where there were no impacts from adversary counter-space activities. To do this, I looked at two specific groups of data: the input factors (surrogates) for representing degradation to combat operations due to a D3SOE, as well as the potential output responses as well. Then, tying these two together, focused on quantifying the impacts of the input factors had on the response factors with regard to metrics of combat effectiveness. So let us start by looking at the factor responses.

The purpose of investigating the factor responses themselves is to look for any additional insight into the operation of the model, as well as any other useful insights that could help determine MANA's viability as a modeling package for my research. My interest here deals more in understanding how the model operates, how input settings effect output responses, what outputs are available for analysis, gaining insight that may help aid in my decision of an M&S package, as well as identifying any lessons learned for incorporation into the final model. To address these interests, I looked at the statistics and distributions of losses for each agent within the simulation, as well as the killer-victim score board. As an example, Figure 101 shows the Blue Tank casualty analysis.

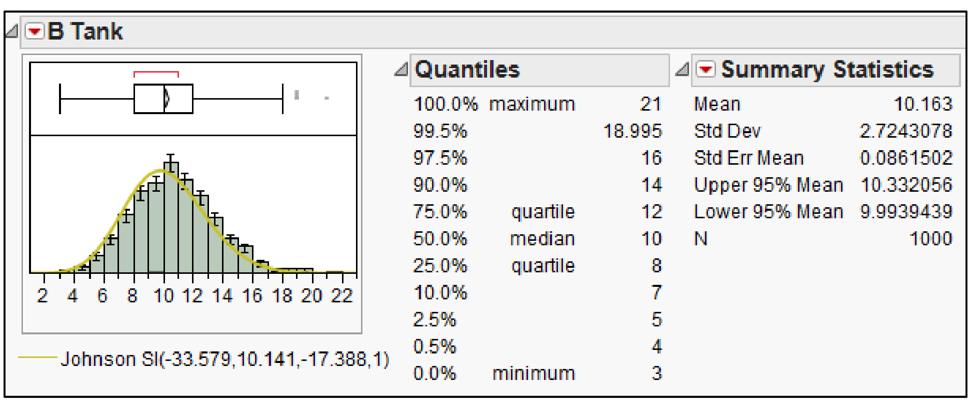
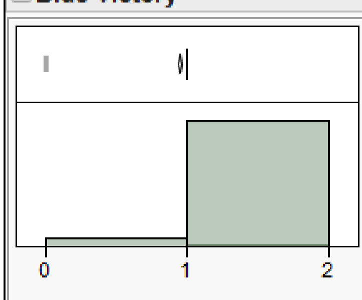


Figure 101. MANA Tank Casualties Summary Statistics

As shown in Figure 101, using JMP I was able to produce detailed statistical analysis of output responses, in this case, Blue Tank Casualties. While this was just one of many available output responses, the results were consistent throughout all the potentials I investigated. For the most part, there was nothing significant learned that was not already understood from my previous analysis. There seems to be ample fidelity in the output data of MANA to perform a wide range of analysis, as well as to support model development.

Next I looked at four potential metrics for combat effectiveness, P_v, LoB, FER, and LER, and then attempted to see if and how MANA could be used to generate data for analysis. While these may or may not be the actual metrics for combat effectiveness used for my research, they were more than adequate to serve in this role for the purpose of this investigation. Luckily, MANA is built as a combat model, so all of these potential metrics are easily calculated. Blue victory can be determined simply by counting the number of times the Red Force lost, i.e., the number of times red losses were >=40. LoB is calculated directly by multiplying the number of time steps at the simulations end by the size of time step. FER can be calculated directly from the outputted Red and Blue losses as well as their respective starting force levels. Likewise, LER can be calculated directly from the Red and Blue losses. So, it seems MANA is fully capable of providing adequate data for analysis of combat effectiveness. Figure 102 shows the base case statistics from JMP for Blue victory.

Blue Victory



Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	1
50.0%	median	1
25.0%	quartile	1
10.0%		1
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	0.946
Std Dev	0.2261308
Std Err Mean	0.0071509
Upper 95% Mean	0.9600325
Lower 95% Mean	0.9319675
N	1000

Figure 102. MANA Summary Statistics of Exploration Run

As shown in Figure 102, during the base case run of my model, Blue forces won roughly 95% of the time, with a 95% CI of (0.932, 0.960). Regardless of the fact that Blue forces won more than I was expecting, the model outputted adequate data to suggest that Victory could be used as a potential metric for combat effectiveness. Unfortunately, by itself, victory does not provide a lot of insight that most decision makers would find useful. For example, due to its discrete nature, victory does not lend itself well to understanding the nuances of variance needed for informed COA comparison, which is the primary purpose of this dissertation. While victory is important, how do you compare one victory to another? Therefore, at best it can serve as a secondary measure of combat effectiveness used in conjunction with another more quantifiable metric, but will likely not be useful by itself other than for screening.

LoB is another metric that does not lend itself directly to decision support. While LoB is arguably an important metric for operational decision support, it should not be considered a primary metric for evaluating combat effectiveness. As with victory, LoB is not useful by itself, and only becomes important when combined with a more insightful metric for evaluating combat effectiveness. Simply put, one does not decide on a COA based on the LoB alone. One must base it on first achieving some other primary metric of combat effectiveness, and then look at minimizing LoB as a secondary comparison metric. Therefore, like victory, this will only be good as a secondary metric for quantifying the impact of D3SOE on combat effectiveness.

Both FER and LER seem to have the potential to serve as primary metrics of combat effectiveness. Both deal with the interaction of losses by each side, and thus, gives an easily understood and quantifiable metric that can be used to compare COAs and alternatives. Thus, both have potential, but because FER takes in account the starting strengths of each side, I believe that FER offers more insight and detail as a primary metric of combat effectiveness than LER. Figure 103 shows the summary statistics of the FER that were provided by JMP.

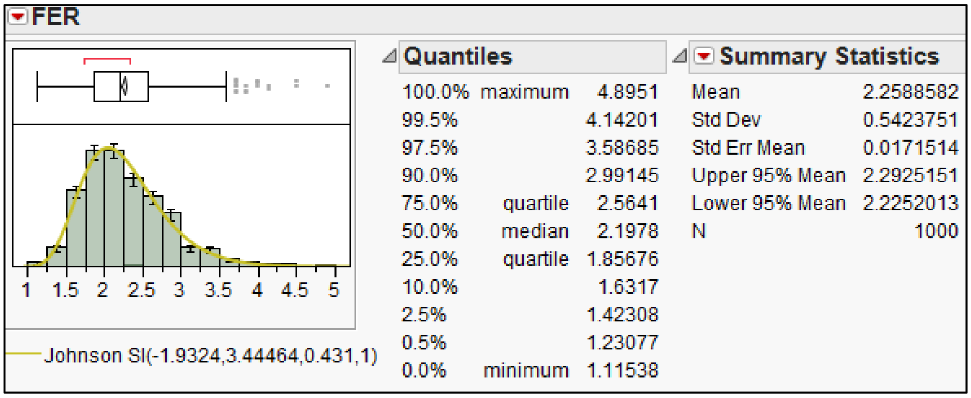


Figure 103. FER as a MANA MOE

As with P_v, using MANA and then JMP to conduct my analysis, I was able to produce detailed statistical analysis of FER in order to judge its fitness for use as a potential metric for combat effectiveness. FER seems to provide a good representation of the outcome of the battle, and in quantifiable terms that are easily understood and conveyed to decision makers. As shown in Figure 103, the distribution shows an approximately normal distribution of outcomes, slightly left skewed with a small right tail, which is expected when considering the high likelihood of Blue P_v. The mean FER of 2.26 shows that for every 1% loss of Blue force structure, the Red force will lose 2.26% of their force strength.

In conclusion, from this initial investigation of MANA, if selected as my M&S package for my research, I will likely use FER as the primary metric for quantifying impacts to combat effectiveness, with both P_v and LoB being used as secondary metrics. In decision support, decision makers can specify a minimum acceptable FER, and use the output of the model to highlight COAs that meet this requirement.

NOLH Design (25700 Runs)

Following a detailed understanding of the base case scenario, it was now time to verify that MANA was capable of supporting the generation and analysis of the output data of a large scale DOE. The DOE would vary the five input factors across the range of potential settings in order to identify their impacts to output responses as well as to the selected metrics of combat effectiveness. Due to MANAs extensive use at NPS, the

execution of the entire 25700 point design took less than a day, and this DOE output data was then imported into JMP. Once in JMP, I tested the usability of JMP to perform: detailed analysis, determine factor significance, identify nonlinearities and higher order interactions, as well as meta-model development. I started my analysis by conducted a stepwise regression for screening then a least squares fit (effects screening). I set FER as my Y variable, and then set the five decision factors (factorial to the 2nd degree and polynomial to the 2nd degree) as my model effects. This captured all main effects and two-way interactions, as well as any non-linearity and higher order interactions across the noise factors, the prediction plot and summary of fit for which can be seen in Figure 104.

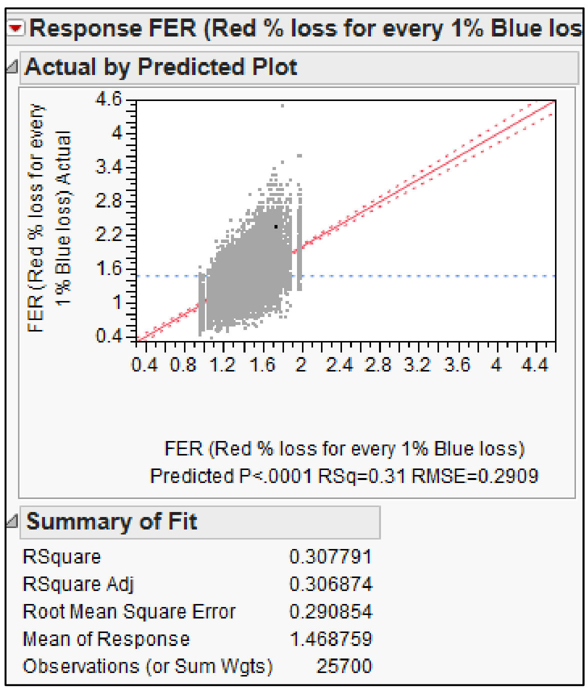


Figure 104. MANA FER Prediction Plot (100 Replications)

As shown in Figure 104, the prediction plot of FER has an adjusted R^2 of .307, which most analysts would consider a weak fit. This is evident by observing the large amount of variability in the prediction plot. While I was expecting a better fit, it is important to understand that the model I built is only an exploratory model, and thus, I am not too concerned with the level of fit thus far. There is entirely too much simplification and uncertainty at this point to take anything but the most simplified and

high level insights from this model. Regardless, I did verify that MANA provides a rich enough output stream allowing for a detailed DOE to conduct higher level analysis and modeling of responses in JMP for use in this dissertation. This prediction of FER allowed me to generate the meta-model shown in Figure 105, which ties the five input factors to a quantifiable measure of combat effectiveness.

Prediction Expression

```
0.47333428114372
+0.00043192015284 *Blue AT Latency
+-0.0014582283022 *Blue HQ Latency
+-0.0008105891975 *Blue Inf Reliability
+0.00019656132609 *Blue Tank Reliability
+-0.0000160197314 *Blue AT Reliability
+0.00374272735472 *Blue HQ Reliability
+-0.000008040607 *Blue UAV Reliability
+-0.000525623044 *Blue Helo Reliability
+0.00018024803954 *Blue Brad Inf Reliability
+0.07122226834542 *Blue Tank Default Speed
+-0.0264123611131 *Blue Arty Default Speed
+0.005389626275 *Blue AT Default Speed
+0.00047026954033 *Blue Helo Default Speed
+0.00826421938212 *Blue Bradly Default Speed
+0.09179780459381 *Blue HQ Higher Ph/dis
+0.23815054904397 *Blue Arty Ph/dis
+ -0.0003212558765
  *Blue Arty Radar Ave Time bet Det
 (Blue AT Latency -13.0038910505837 )
+*[(Blue Helo Default Speed-67.5000778210117 )
   *-0.0000967934007 ]
 (Blue HQ Latency -25.0038910505837 )
+*[(Blue HQ Reliability-75.0001556420234 )
   *-0.0000389799804 ]
 (Blue HQ Latency -25.0038910505837 )
+*[(Blue HQ Higher Ph/dis-0.4003112840467 )
   *0.00026548742769 ]
 (Blue Inf Reliability-75.0001556420235 )
+*[(Blue Helo Reliability-75.0001556420235 )
   *-0.0000101274732 ]
 (Blue Tank Reliability-75.0001556420234 )
+*[(Blue AT Reliability-75.0001556420234 )
   *-0.0000444226714 ]
```

Figure 105. Meta-Model of FER (partial)

During my research I discovered that Treml (2013) also encountered a similar problem where he was getting a fairly low R^2. He adjusted this R^2 by calculating the mean response of each MOE across the 460 replications, which yielded a new R^2 of .813. While this method was successful in vastly improving the explanatory power of his model, it also removed all of the variability across his design points, which is often sought in combat models. Thus, while this method was good for determining the

expected mean FER for any give setting of the five input factors, it was no longer useful in capturing the uncertainty or variability. To see if this method could be used with my data in order to improve the model fit, I conducted a similar procedure, and took the means of my responses across the 100 replications at each design point and re-ran my analysis, which can be seen in Figure 106.

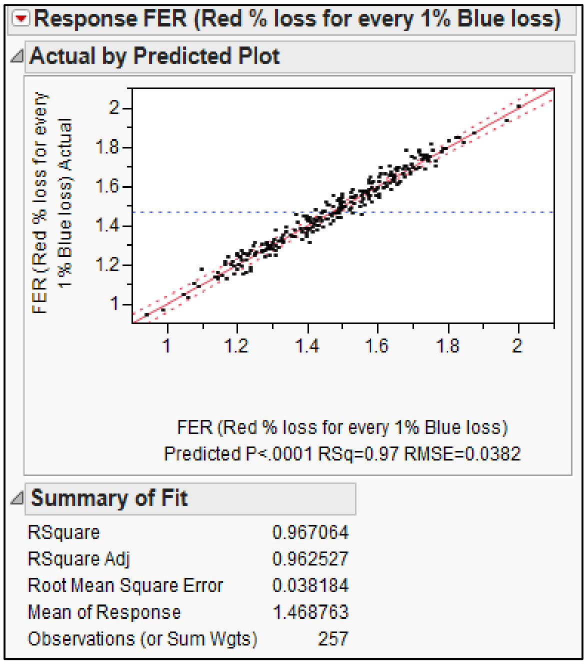


Figure 106. MANA FER Prediction Plot (Means of Replications)

As shown in Figure 106, by using the means of each of the 100 replication sets, I was able to take a poor fitting model with an adjusted R^2 of 0.307 and transform it into an excellent fitting model with an adjusted R^2 of 0.96. Again, while the meaning of the replications significantly hampers our ability to capture the variability of the combat model, it does show that a good fitting model is possible if means are more important than capturing the true variance. Although variability of the potential outcomes is often just as important as the mean, there are often times when means are sufficient. While it is too early to determine if this issue will impact my research, it will be important to capture and address it again once the final model is built. Regardless, I believe that even with the reduced capability of this model to capture the variability of potential outcomes it still has

some usefulness in addressing the mean likelihood, and thus, is appropriate for this initial investigation. Using the prediction from Figure 105, I investigated which input factors and interactions were the most significant. The sorted parameter estimates for this investigation can be seen in Figure 107.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Blue Tank Default Speed	0.0712223	0.000783	91.01	<.0001*
Blue HQ Reliability	0.0037427	0.000125	29.89	<.0001*
Blue Arty Ph/dis	0.2381505	0.01043	22.83	<.0001*
Blue Arty Default Speed	-0.026412	0.001252	-21.09	<.0001*
Blue Arty Radar Ave Time bet Det	-0.000321	2.722e-5	-11.80	<.0001*
Blue HQ Higher Ph/dis	0.0917978	0.007826	11.73	<.0001*
(Blue Tank Default Speed-11.0006)*(Blue Tank Default Speed-11.0006)	-0.004892	0.000431	-11.34	<.0001*
Blue HQ Latency	-0.001458	0.000136	-10.72	<.0001*
Blue Bradly Default Speed	0.0082642	0.000783	10.56	<.0001*
(Blue Tank Default Speed-11.0006)*(Blue Bradly Default Speed-11.0006)	0.0034834	0.000367	9.48	<.0001*
(Blue HQ Reliability-75.0002)*(Blue HQ Reliability-75.0002)	-8.436e-5	0.00001	-8.45	<.0001*
(Blue Arty Ph/dis-0.50008)*(Blue Arty Radar Ave Time bet Det-125.004)	-0.001319	0.000157	-8.40	<.0001*
Blue Inf Reliability	-0.000811	0.000125	-6.47	<.0001*
Blue AT Default Speed	0.0053896	0.000894	6.03	<.0001*
(Blue Tank Reliability-75.0002)*(Blue Tank Reliability-75.0002)	-5.757e-5	1.032e-5	-5.58	<.0001*
(Blue HQ Reliability-75.0002)*(Blue Tank Default Speed-11.0006)	0.0002965	0.000056	5.29	<.0001*
(Blue UAV Reliability-75.0002)*(Blue Brad Inf Reliability-75.0002)	4.3067e-5	8.935e-6	4.82	<.0001*
(Blue Tank Reliability-75.0002)*(Blue AT Reliability-75.0002)	-4.442e-5	9.546e-6	-4.65	<.0001*
(Blue HQ Latency-25.0039)*(Blue HQ Reliability-75.0002)	-0.000039	9.126e-6	-4.27	<.0001*
Blue Helo Reliability	-0.000526	0.000125	-4.20	<.0001*
(Blue AT Latency-13.0039)*(Blue Helo Default Speed-67.5001)	-9.679e-5	0.000024	-4.04	<.0001*
(Blue Arty Radar Ave Time bet Det-125.004)*(Blue Arty Radar Ave Time bet Det-125.004)	2.0603e-6	5.129e-7	4.02	<.0001*
(Blue AT Default Speed-9.50008)*(Blue AT Default Speed-9.50008)	-0.002118	0.000529	-4.00	<.0001*
(Blue HQ Reliability-75.0002)*(Blue Arty Ph/dis-0.50008)	0.0030302	0.000798	3.80	0.0001*
(Blue HQ Higher Ph/dis-0.40031)*(Blue Arty Ph/dis-0.50008)	0.1637925	0.047525	3.45	0.0006*
Blue Helo Default Speed	0.0004703	0.000139	3.38	0.0007*
(Blue Arty Default Speed-7.50008)*(Blue Arty Radar Ave Time bet Det-125.004)	-0.000046	1.759e-5	-2.62	0.0089*

Figure 107. MANA parameter Estimates for Model Fit

Even though this is a fairly large list of significant factors, 27 in all, it is easy to see that just eight factors and their higher order interactions dominate the response. Thus, it is possible to use this sorted list as a screening tool, then selecting a more detailed design, focus on just these eight factors to explore the tradespace in more depth. Although the factors that I expected to be significant were not, the manner in which I developed and implemented the model seriously undervalues the value of intelligence collection assets due to the limited amount of time given to build the combat picture and execute preparatory fires prior to combat. These are issues that can be addressed in future versions of the model, but regardless of the outcome of this basic analysis, it is evident that MANA is capable of producing robust data with enough depth to allow for valuable analysis in support of my research.

g. Findings

Overall, MANA provides a robust enough environment to more than adequately meet the needs I have for my dissertation. Following the investigation, I conducted a qualitative assessment of MANA's ability to meet each of my primary and secondary research needs, and the scoring of this assessment can be seen in Table 73. Following the investigation of all potential M&S packages, this assessment of MANA will be used to compare the three potential alternatives.

Table 73. MANA Assessment Table

Weighted Decision Matrix		
Weight	Factors	MANA
6	Ability to Simulate a D3SOE	3
5	Support Availability	5
5	Cluster Access	5
5	Ease of Use	5
4	Rapid Development	4
4	Existing Models	5
4	Ease of Analysis	4
4	Output Data Density	4
3	Learning Curve	4
3	Behavior Monitoring	4
3	DOE Tools Available	5
2	Ease of DOE Execution	5
	Total Value	200

As shown in Table 73, while I do not believe that MANA is well suited for modeling the impacts from a D3SOE, it was well suited to support my work across all other areas when considering my primary and secondary research considerations. Couple this with the fact that I believe that there are adequate alternative factors in MANA to represent all of the effects I am trying to model through the use of surrogates, and I am more than confident that MANA is capable of meeting nearly all my research needs without much additional effort.

2. Exploration of JDAFS

JDAFS has been in development on and off for almost a decade, and its creator, Dr. Arnie Buss, is a member of the MOVES faculty here at NPS. The proximity of Dr.

Buss provides a source of resident experience and knowledge that could significantly aid my research. JDAFS was initially designed as a fires allocation tool but was later expanded to perform a much broader set of M&S tasks. JDAFS is a low resolution agent based simulation framework that focuses on supporting users who need a fast, flexible, and customizable M&S package. JDAFS nature as a DE simulation "leads to fast execution times, which enable the analyst to quickly explore the parameter space for the desired situation" (Buss and D. K. Ahner 2006, 4). I initially had little knowledge of or experience with JDAFS, but because of its availability and resident expertise, as well as the fact that it was a DE simulation, a rarity, I was more than curious about its potential in supporting my work.

a. Initial Observations

Like MANA, my initial investigation of JDAFS was focused on determining the usability of the model, how it operated, and how easily it could be developed and modified. While my initial feelings regarding JDAFS as a potential M&S package were questionable, I believed that JDAFS had enough potential to model a D3SOE that it was worth investigating in more depth. When it comes to usability, JDAFS is not the most user friendly or elegant M&S package I have seen, nor does it have what I would call a quick learning curve, but it is fairly easy to implement and run with a simple UI that is easy to navigate. While it comes with a fairly detailed user manual, its nature as a simulation framework leaves much of the simulations development and utilization requirements to the user. Thus, while JDAFS is extremely flexible in that a user can add any functionality desired, this flexibility comes with a cost, forcing a user to code nearly all of this functionality into the model. While this could be mitigated by the re-use of existing models that have the functionality I was interested in, there were simply none available at the level of complexity I needed. Thus, the use of JDAFS as my M&S package would come with a significant amount of time and effort to prepare it for use.

b. Potential Factors for Representing a D3SOE

My initial investigation included reviewing the factors in JDAFS that I thought I could use to model the impacts from a D3SOE. Because JDAFS is a framework, I began

my review by experimenting with the most complex example model I could find to avoid developing an entire model just for an investigation. Like most M&S packages, there are no direct or specific factor settings for degrading communications, ISR, and GPS in JDAFS. Luckily, this makes no difference with regard to JDAFS because any functionality needed can be added, at least to the extent that the foundational rules of JDAFS allow. Thus, as long as the underlying rules are not violated, it should be possible to add any needed functionality and appropriate factors. While this could potentially be cumbersome, if the user has the resources, JDAFS seems to have ample flexibility to represent the expected impacts and effects of a D3SOE. For consistency, potential JDAFS factors will be binned as before, into three distinct groups: communications degradation, ISR degradation, and PNT degradation. Recall that JDAFS has no set factors; thus, I will discuss in more broad terms how JDAFS can be used to demonstrate the effects of a D3SOE on combat operations.

Communications Degradation

My initial investigation of JDAFS regarding communications degradation led me to believe that JDAFS may not be capable of accurately modeling the effects I needed. After consulting with JDAFS experts, it seems that this is indeed the case, and that representing accurate communications and then degrading them will not be possible with JDAFS. Because every agent in an opposing force shares the same Common Operating Picture (COP) without delay or inaccuracies, without actual communications links to degrade it will be difficult to institute any type of degradation that closely resembles actual combat. I would need to identify and code a means to induce error into this COP, to include slowing and degrading the flow of information, as well as reducing the amount of information shared. While this should be possible, it induces a high amount of uncertainty regarding the usability of JDAFS to meet my needs. If the inability of JDAFS to accurately model communications holds true, it may be unusable for my purposes.

ISR Collection Degradation

Because JDAFS has no communications links, I was not able to degrade communications to represent a degradation of collection assets as done previously.

Detections made by an agent in JDAFS are known instantly by all friendly forces, without error, and there does not seem to be a way to induce lag, inaccuracies, or degradation of the collection capability directly. Thus, to induce impacts from the degradation of ISR capabilities in JDAFS, I needed to identify alternative methods that could be modified to simulate the needed effects. I identified two potential ways to achieve the effects of ISR degradation, but these would again require abstract, counter-intuitive implementation to simulate the desired impacts. While the complexity of this implementation is not a show stopper, it should be understood before JDAFS is used.

- Destroying Collection Assets

First, for systems with representative agents in the model such as UAVs, HAASs, and SmallSats, it is possible for the adversary to destroy them, and thus the degradation of the system would be induced into the model directly. This addition to the model could potentially be represented as a Red ADA unit with a specialized munition to target UAVs or SmallSats, like an SA-18. So, it looks as if I should be capable of modeling the loss of the UAVs through destruction, but is it is possible to degrade the UAVs in other ways? For example, how can I represent a partial loss of capability? To model this functionality will require using other methods, likely through the degradation of sensors.

- Degrading Sensors

By manipulating a sensors' probability of detection, time between detections, or each of these two factors' interactions with range, it is possible to represent various degrees of degradation of the specific collection asset. As long as adequate and representative range-based sensors are used, this needed functionality should be pretty straightforward to model. All agents will need to be provided more realistic sensors to account for different probabilities-based on the type of system (vehicle/personnel), but again, the addition of this functionality to the model should be fairly simple. Additionally, for me to use this model, I would need to add in extra sensors to represent Battalion Intel and possibly even higher headquarters ISR and SIGINT assets and use a range-based probability of detection sensor. These detection probabilities could then be modified by some unknown amount to account for the level of collection degradation needed to simulate degradation of ISR systems.

PNT Degradation

Like other M&S packages, there was no direct way to induce the type of degradation I was looking for because the SA picture of all agents in JDAFS is known instantly by all friendly forces once it is detected, without error. Agents have perfect SA of all friendly forces as well as everything that is detected. Thus, there is no way to directly induce positional error, so like we will look to see if we can mimic locational inaccuracies in other ways. The representation of PNT degradation can be done similarly to how we did it with MANA, namely by manipulating movement speed and targeting accuracy factors of indirect fire systems.

- Movement

Because of its nature as a DE simulation, JDAFS is somewhat limited in how it executes movement. JDAFS uses a value score in the move manager to determine where the units will attack, based on what has been detected, the Probability of Kill ($P_{k)}$, and the subjective value of the targets within range. Unfortunately, JDAFS has no other personality type attributes to help determine movement other than these simple movement rules. While I can adjust movement speed, and use it to serve as a surrogate for locational degradation, JDAFS is lacking in every other way in representing actual combat maneuver. For example, there is no associated value to maintaining unit cohesion, or mass, when moving. While I could likely add this functionality given adequate resources, especially time, consideration must be made on the feasibility of this investment with regard to the work required. Additionally, the number of agent interactions needed to adequately model movement that can account for mass and other principles, to include interactions with terrain, would significantly increase the number of events of the model. Thus, many of the advantages of a DE model would be negated due to the increased complexity of the model. While these are mostly usability aspects of JDAFS, they must be considered when selecting an M&S package for use in my research.

- Targeting

Targeting in JDAFS is much more intuitive than movement, and other than the requirement to physically code each and every weapon-to-target range-based P_k matrix, it

seems to be pretty straightforward. Each engagement is based on the value assigned to the target type, and if there are multiple targets available in a given instance, JDAFS will select the highest value target. Then, after calculating range, it will look up the P_k for that weapon-target combo and assess whether it is a hit or not. Thus, the probability of hit rate per discharge seems to be a good factor for partially representing the impacts from degraded targeting information for indirect fires.

In conclusion, based on this assessment, I believe JDAFS has enough flexibility to provide some of the factors needed for use in my research. While I will not be able to model communications degradation effectively, at least not directly, it should be possible to find some other factors that could indirectly act as a surrogate for these effects. For degradation of PNT, I should be able to use movement speed to represent degradation of positional and destination accuracy for all moving agents, as well as hit rate per discharge to represent the impact of degraded targeting data for all indirect fire agents. Finally, I will use average time between detections (detection range) to represent the impacts of degraded ISR collection on collection assets; although I will need to drastically increase these factors to account for any communications degradation that cannot be modeled directly. The combination of these input factors should give me a decent capacity to represent the effects and impacts from a D3SOE on combat operations.

c. Potential Output Responses for Combat Effectiveness

With potential input factors identified, it is now time to investigate the available output responses JDAFS provides in order to determine its feasibility for use in my research. Because JDAFS was designed to support analysis of the allocation of military indirect fires, its outputs include a host of relevant combat statistics to include force losses, losses by source, as well as killer-shooter information. While JDAFS' output is not as user friendly as other M&S packages, everything that is needed to conduct further analysis is present, even though it will require a fair amount of post processing to prepare it for import into JMP. Thus, it seems that JDAFS should be capable of providing more than adequate output data needed to enable a large-scale DOE and drive meta-model development, as needed for my research.

d. Model Development

As before, the purpose here is to look at how easy JDAFS is to manipulate, to create new agents, and to modify their attributes to achieve the behaviors and effects I seek to imitate. For this exploration, I started with a toy model provided in the example files that accompany JDAFS. Initially, I choose what I considered the most complex ground combat model available, though it was not nearly as detailed as other models I investigated. I set out to look at a few specific concepts within JDAFS to assess its capabilities as well as its strengths and weaknesses.

Once JDAFS is executed, a UI tool opens, which allows users of JDAFS to load and run a model, generate output data, and do some simple execution level tasks before running the model. What is most notable thus far is that JDAFS does not allow one to make any changes to the model through the UI; it exists solely to allow a user to run a model. In JDAFS, all agent activities and behaviors are outlined in two other documents, which I am able to modify to affect agent attribute changes. The first is the SampleInput.mdb database file, and the second is the xml file itself. The Access database file is where all changes to the model can be made easily, and then JDAFS loads the database file by creating an xml file. So the Access database acts as the UI for model development, and to implement any changes during model development either the database or the xml file must be updated. The Access database can be seen in Figure 108.

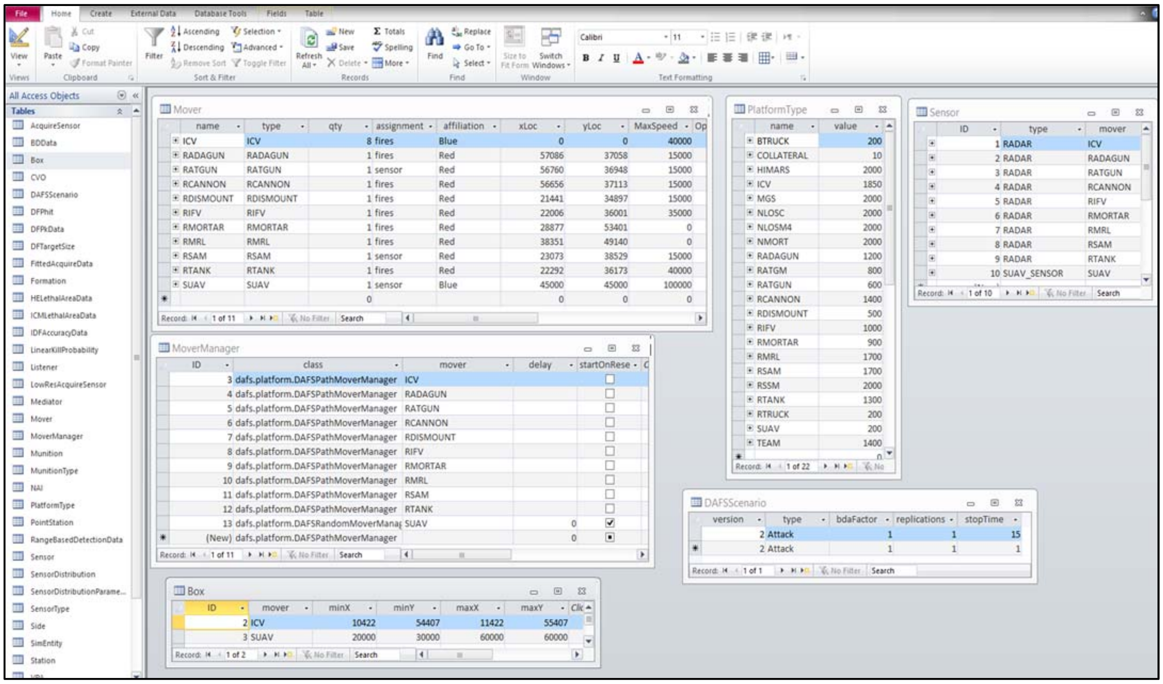


Figure 108. JDAFS Access Database

By modifying the Access database directly, and playing with certain aspects of each agent, I was able to change starting locations, the number of forces, quantity and capabilities of munitions, P_k, as well as numerous others factors. Model development was pretty straightforward once a user learns where everything is in the xml file, and I started off by adding in a search area for the UAV to move in a random search pattern. I then modified the Red forces AT-10 weapon and allowed it to target the Blue UAV. Through trial and error over the course of a few weeks, I was able to apply numerous other modifications to agents in order to determine their fitness for use to demonstrate the impacts of a D3SOE on combat operations. I ended this development with a fairly simple model that did not differ drastically from the original model and was comprised of six Blue Improved Combat Vehicles (ICV) and a single Blue UAV, pitted against eight Red fires systems (tank, Arty, Mortar, AT, IFV, Dismounts, MRL), and two Red Sensors. Figure 109 shows the JDAFS UI mid run.

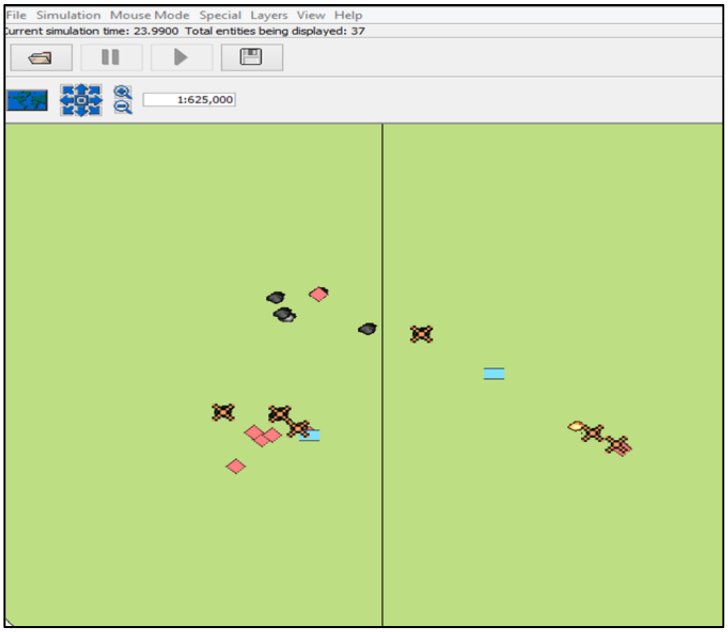


Figure 109. JDAFS UI Window

As shown in Figure 109, JDAFS comes with a fairly simple UI, allowing the developer to run a model and generate output data for analysis. While not as graphically appealing as other M&S packages, it is sufficient for its purpose. The model runs quickly, often too fast to observe most agent behaviors, fortunately, by selecting the Verbose After Run box in the Simulation Parameters window, the model will run much slower, allowing the developer to watch agent behaviors during execution. This is extremely useful during validation and troubleshooting. Running the model and setting up multiple replications was also fairly straightforward. In this case, I ran the model 100 times, and the execution time was less than 1 min, with an additional 1 min to compile the output data and create the output database. Although the JDAFS model was less complex than other models investigated, the advantage of a model that runs 60 times faster is notable.

e. DOE

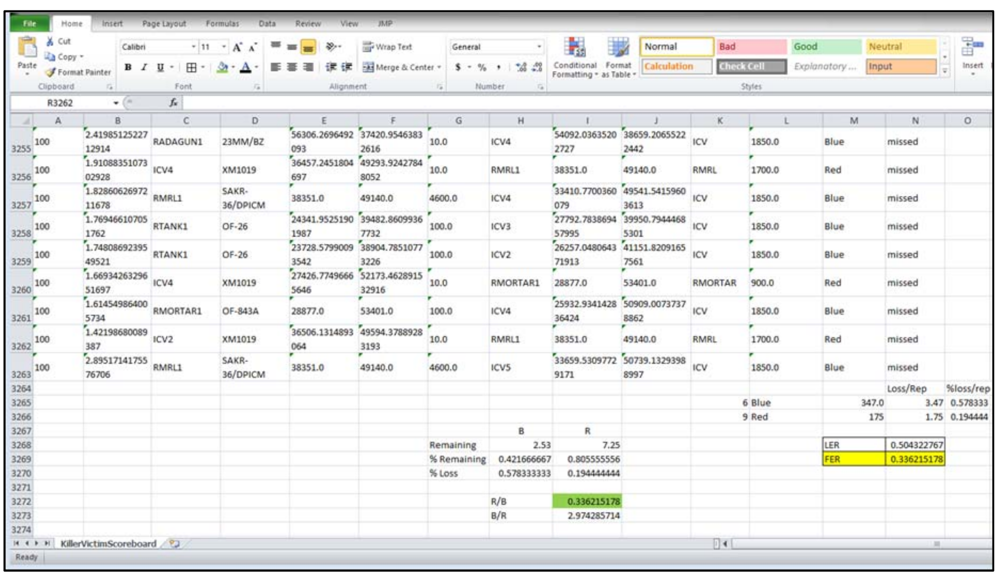
My biggest concern regarding JDAFS was whether or not it could produce the quantity and quality of data I needed to execute a large-scale DOE. While JDAFS can produce multiple runs of the same design point with different random number seeds, there is not a fully developed tool I can use to execute a full DOE. While there are scripts

available that could read a design from one file, and create the associated xml document for that run, they are outdated, and would need a fairly significant update to become viable. Even so, this method is neither efficient nor elegant. For a 257 design point design, this method would literally create an xml file for each of these designs and then run each 100 times with different seeds, producing a separate output file. This output would then require additional scripts to format and post-process the data before it could be brought into JMP for analysis. It is for these reasons, namely the lack of the scripts needed to run JDAFS, that I was unable to execute a full DOE during this exploration.

f. Analysis

The purpose of this section is not focused on analysis per say, but more on "how well" JDAFS supports my research needs for analysis. Unfortunately, due to the significant requirements needed to develop a usable JDAFS model, I was unable to achieve many of the analysis demonstrations shown in the previous section. Even so, I was able to conduct a thorough enough exploration to confirm that JDAFS does produce adequate output data for use in my research. Though this output data will require a fair amount of post processing to prepare it for import into JMP, the amount of effort needed to do so is minimal. An example output file provided by JDAFS can be seen in Table 74.

Table 74. JDAFS Output Database File



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
3255	100	2.4198512522712914	RADAGUN1	23MM/BZ	56306.2696492093	37420.95463832616	10.0	ICV4	54092.03635202727	38659.20655222442	ICV	1850.0	Blue	missed	
3256	100	1.9108835107302928	ICV4	XM1019	36457.2451804697	49293.92427848052	10.0	RMRL1	38351.0	49140.0	RMRL	1700.0	Red	missed	
3257	100	1.8286062697211678	RMRL1	SAKR-36/DPICM	38351.0	49140.0	4600.0	ICV4	33410.7700360079	49541.54159603613	ICV	1850.0	Blue	missed	
3258	100	1.769466107051762	RTANK1	OF-26	24341.95251901987	39482.86099367732	100.0	ICV3	27792.783869457995	39950.79444685301	ICV	1850.0	Blue	missed	
3259	100	1.7480869239549521	RTANK1	OF-26	23728.57990093542	38904.78510773226	100.0	ICV2	26257.048064371913	41151.82091657561	ICV	1850.0	Blue	missed	
3260	100	1.6693426329651697	ICV4	XM1019	27426.77496665646	52173.462891532916	10.0	RMORTAR1	28877.0	53401.0	RMORTAR	900.0	Red	missed	
3261	100	1.614549864005734	RMORTAR1	OF-843A	28877.0	53401.0	100.0	ICV4	25932.934142836424	50909.00737378862	ICV	1850.0	Blue	missed	
3262	100	1.42198680089387	ICV2	XM1019	36506.1314893064	49594.37889283193	10.0	RMRL1	38351.0	49140.0	RMRL	1700.0	Red	missed	
3263	100	2.8951714175576706	RMRL1	SAKR-36/DPICM	38351.0	49140.0	4600.0	ICV5	33659.53097729171	50739.13293988997	ICV	1850.0	Blue	missed	
3264														Loss/Rep	%loss/rep
3265											6	Blue	347.0	3.47	0.578333
3266											9	Red	175	1.75	0.194444
3267								B	R						
3268							Remaining	2.53	7.25				LER	0.504322767	
3269							% Remaining	0.421666667	0.805555556				FER	0.336215178	
3270							% Loss	0.578333333	0.194444444						
3271															
3272								R/B	0.336215178						
3273								B/R	2.974285714						
3274															

As shown in Table 74, JDAFS produces adequate output data, and other than requiring more post-processing, it will be capable of producing detailed enough data for my work. Because I was unable to perform the large-scale DOE as seen previously, I was unable to produce the data required for analysis. Thus, I did not show any of the statistical analysis as I did in the previous section. Fortunately, once the JDAFS scripting issues are resolved and I am able to conduct a full DOE, it is evident that JDAFS is capable of producing robust enough data with enough depth to allow for valuable analysis in support of my research.

g. Findings

Overall, JDAFS is a fairly flexible environment that can be used for a host of modeling activities, to include modeling for my research. Following this investigation, I conducted a subjective assessment of JDAFS' ability to meet each of my primary and secondary research needs, and the scoring of this assessment can be seen in Table 75.

Table 75. JDAFS Assessment Table

Weighted Decision Matrix		
Weight	Factors	JDAFS
6	Ability to Simulate a D3SOE	2
5	Support Availability	3
5	Cluster Access	3
5	Ease of Use	1
4	Rapid Development	2
4	Existing Models	2
4	Ease of Analysis	2
4	Output Data Density	2
3	Learning Curve	2
3	Behavior Monitoring	2
3	DOE Tools Available	3
2	Ease of DOE Execution	2
	Total Value	99

As shown in Table 75, I felt that JDAFS was not well suited for modeling the impacts from a D3SOE, nor was it well suited to support my work when considering my primary and secondary research considerations. While I believe JDAFS has the potential

to meet most of my research needs given adequate time and resources, there is a high level of uncertainty that must be considered if selecting JDAFS for use.

3. Exploration of SEAS

SEAS is an agent-based M&S package that has been in development and actively used by the Air Force Space and Missile Systems Center for the past 20 years. SEAS is a constructive, time-step, mission level M&S package that supports military operations research in support of "developmental planning and Pre-Milestone 'A' acquisition decisions for military space systems. SEAS has proven to be a valuable military ops research tool by enabling exploratory analysis of new system concepts, system architectures, and Concepts of Operations (CONOPS) in the context of joint warfighting scenarios" (TeamSEAS 2017). Other than the information listed on the DOD M&S Catalog, I was unable to gather much data regarding SEAS. Unlike MANA and JDAFS, SEAS is not openly available, and thus, I was initially unable to make any assessments of SEAS' potential usability for my research. After making contact with the Air Force Program Officer as well as Army users, primarily in the space professions, I was able to get a copy of SEAS for use in my exploration. Despite the limited access to SEAS and lack of resident expertise at NPS, its status as an actively used M&S package within the DOD to investigate space and C4I systems had me more than curious about its potential for modeling a D3SOE.

a. Initial Observations

Like the two preceding M&S packages, my initial investigation of SEAS was focused on getting a feel for the usability of the model, how it operated, and how easily it could be developed and modified. SEAS is fairly easy to implement and run, and using its intuitive UI and IDE make it is easy to execute incremental development. While SEAS comes with a detailed user manual, its nature as a simulation framework leaves much of the simulations development and utilization requirements to the user. So, like JDAFS, SEAS offers an exceptional amount of developmental flexibility but at the cost of time and resources needed to code the needed functionality. While this issue could be mitigated by the use of existing models, all models currently being used by both Army

and Air Force planners are classified, and thus not available to support my work. Thus, when considering SEAS as a potential M&S package, considerations for increased model development requirements and coding to prepare the model must be accounted for.

b. Potential Factors for Representing a D3SOE

My initial investigation included a look at the factors in SEAS that I thought I could use to model the impacts from a D3SOE. Because this is a framework, I experimented with the most complex example model I could find to avoid developing an entire model just for an investigation. Unlike MANA and JDAFS, there are specific factor settings for degrading communications, ISR, and GPS in SEAS. Thus, there would be no need for surrogate factors to represent the impacts of a D3SOE. Unfortunately, the simple model that was available for me to investigate did not include the needed functionality, and without a much more complex and detailed model to work from, I would need to code this functionality from scratch. Thus, while SEAS can represent the impacts and effects I am looking to manipulate, I was unable to do so during this investigation. Regardless, while the use of SEAS could be cumbersome, there seems to be ample flexibility to represent the expected impacts and effects of a D3SOE if additional time is available for the developmental effort. Like the previous investigations, potential factors in SEAS will be binned into three distinct groups, communications degradation, ISR degradation, and PNT degradation.

Communications Degradation

Through my investigation, it is more than evident that SEAS has an exceptionally rich and detailed capability to model communications. Unlike many other M&S packages, SEAS does not require the use of surrogate factors to represent impacts to communications, it can do so directly. Not only does SEAS model communication links in great detail, but it can also model the degradation of communications through the integration and modeling of adversary counter-space capabilities. Unfortunately, because SEAS is a framework and I do not have access to an unclassified model, I would need to code all this functionality from scratch. While SEAS seems to be the most capable of the M&S packages investigated with regard to modeling communications degradation, a

significant amount of developmental effort would be needed to build a model. Thus, consideration for time and resources available should be made when assessing the feasibility of SEAS for use as a potential M&S package, especially if an unclassified model cannot be found.

ISR Collection Degradation

As with communications degradation, SEAS is able to model ISR collection assets in great detail, as well as the ability to model adversary counter-space capabilities and effects that could impact these systems, to include kinetic and non-kinetic weapons. In fact, the resolution and detail of SEAS is far greater than what is actually needed, something that should typically be avoided, and will need to be considered later. Thus, it again seems that SEAS is the most capable of the M&S packages investigated, and it is extremely well suited for modeling the impacts to ISR due to the degradation of collection assets. Yet, as we saw with communications degradation, a significant amount of developmental effort would be needed to build a model, and must be considered when assessing the usability of SEAS for my research. So, as before, unless an unclassified model can be found, the use of SEAS may not be feasible.

PNT Degradation

Unlike most M&S packages, SEAS is capable of degrading the capabilities of U.S. PNT signals directly through the model, inducing both locational and timing errors. This can be done in numerous ways; everything from impacting the GPS satellites directly to the use of terrestrial based GPS jammers is possible. What is evident is that once again, SEAS provides an extremely robust environment in which to degrade the capabilities of space based PNT. Thus, SEAS again seems to be the most capable of the M&S packages investigated, and is well suited for modeling the impacts to PNT due to the degradation from operations in a D3SOE. Unfortunately, as we saw previously, it would again require a significant amount of time and effort in order to build a model.

In conclusion, based on this analysis, I believe SEAS has significant flexibility and depth to more than adequately represent the effects in which I am trying to simulate in my research. SEAS allows the user to model the systems, counter-space capabilities,

and effects on communications, ISR collection, and PNT degradation directly, without modification or the use of surrogates. This is extremely valuable to my work, and a serious consideration when selecting an appropriate M&S package. The combination of these factors gives me the best capacity to represent the effects and impacts from a D3SOE on space systems and space operation.

Unfortunately, I am not interested on the impacts of a D3SOE on space systems, I am interested on the impacts they have on metrics of combat effectiveness, from the perspective of the ground force. Thus, the ability of SEAS to translate these space operational impacts into impacts on ground force is important. While everything regarding SEAS discussed thus far shows a significant capability of SEAS to model a D3SOE, it is important to understand that this is from an Air Force perspective, whose measures of combat effectiveness differ greatly from Army measures of combat effectiveness. Therefore, caution is advised when considering SEAS as a potential M&S package. If SEAS is selected, verifying that ground combat operations are modeled correctly and to the depth and level of detail needed will be essential. Likewise, verifying that the impacts to combat effectiveness are adequate and using measures of operational effectiveness relative to ground combat will also me necessary.

c. Potential Output Responses for Combat Effectiveness

With the potential of SEAS to provide adequate input factors to represent communications, ISR collection, and PNT degradation established, it is now time to investigate the available output responses SEAS provides to determine its feasibility for use in my research. Because SEAS was designed to support analysis and comparison of emerging space systems and technologies in terms of impacts to Air Force measures of combat effectiveness, its outputs include a host of relevant combat statistics. These statistics include responses like force losses, losses by source, as well as a host of space and communications specific information not typically covered in other M&S packages. The SEAS output files are organized fairly well, and require only minor modifications to get them in a form suitable for importing into JMP. There is more than ample information available through the various output files to conduct analysis to the level that is required

for my work. In fact, there is more than enough information to conduct more detailed analysis, specifically regarding factors of communications and C4I. Thus, SEAS should be capable of providing more than adequate output data needed to enable a large scale DOE and drive meta-model development as needed for my research.

d. Model Development

SEAS uses a fairly well developed UI that allows a user to load, run, generate output data, and to do some simple execution level tasks before running the model. Like JDAFS, SEAS does not allow a user to make any changes to the model through the UI; it exists solely to allow for the running of the model and generation of output data. While this is arguably only a minor inconvenience, it does impact the usability of SEAS, specifically when considering the significant amount of iterative development that will be needed to build the model. All agent activities and behaviors in SEAS are outlined in a .war file, and modification or incremental development of the model is done through the Eclipse IDE. The SEAS Eclipse IDE can be seen in Figure 110.

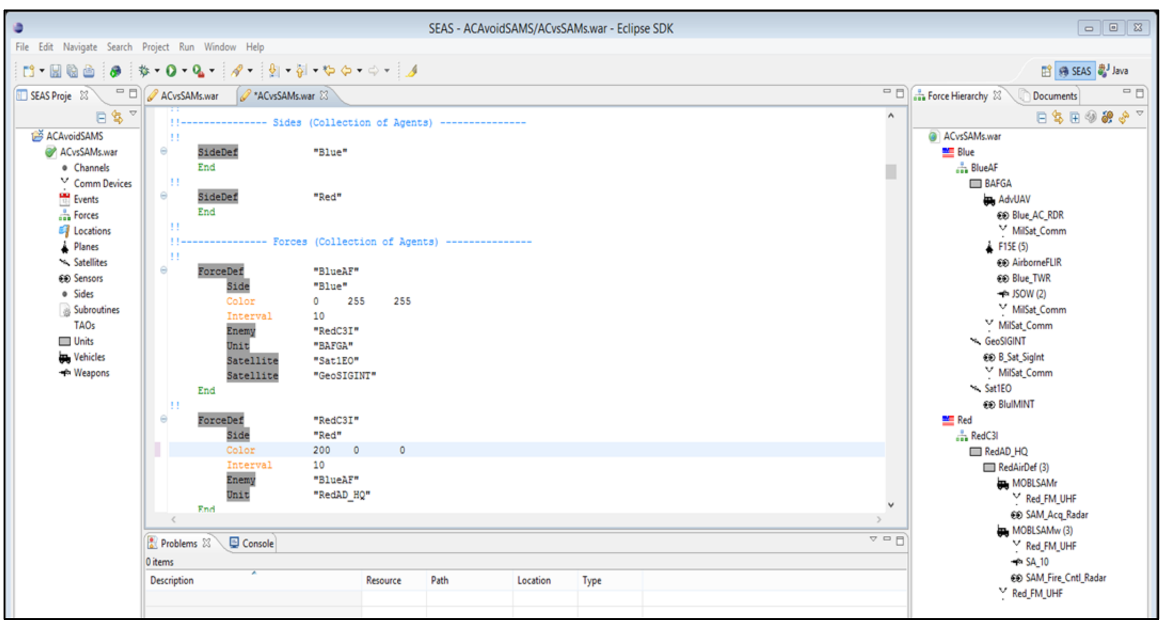


Figure 110. SEAS Eclipse IDE Window

As with MANA and JDAFS, the purpose here is to look at how easy SEAS is to manipulate, to create new agents, and to modify their attributes to achieve the behaviors and effects I am looking to imitate. Because I was somewhat concerned about the ability of SEAS to model ground combat operations, I choose to look at two different types of models. First, I looked at a ground maneuver model that was provided in the example files that accompany SEAS to investigate how SEAS modeled ground combat. Second, I looked at a more traditional SEAS model, which included UAVs and Radar sites, to investigate the models capacity regarding collection assets and communications. By modifying the .war file, and playing with certain aspects of each agent, I was able to change starting locations, the number of forces, quantity and capabilities of munitions, P_k, as well as others factors, which were all pretty straight forward in the well-organized and documented examples used.

Through trial and error over the course of a few weeks, I was able to apply numerous modifications to agents to determine their fitness for use. I ended this development with a pair of fairly simple models. The first was the Air model, which did not differ drastically from the original model, and was comprised of a Blue UAV, a squadron of Blue strike fighters, pitted against three ADA sites. One can see a screenshot of the Air simulation UI in Figure 111. The second was the ground model, and it was altered significantly to comprise of a four Blue tank companies executing a flanking maneuver against three defending and better armed Red tank companies.

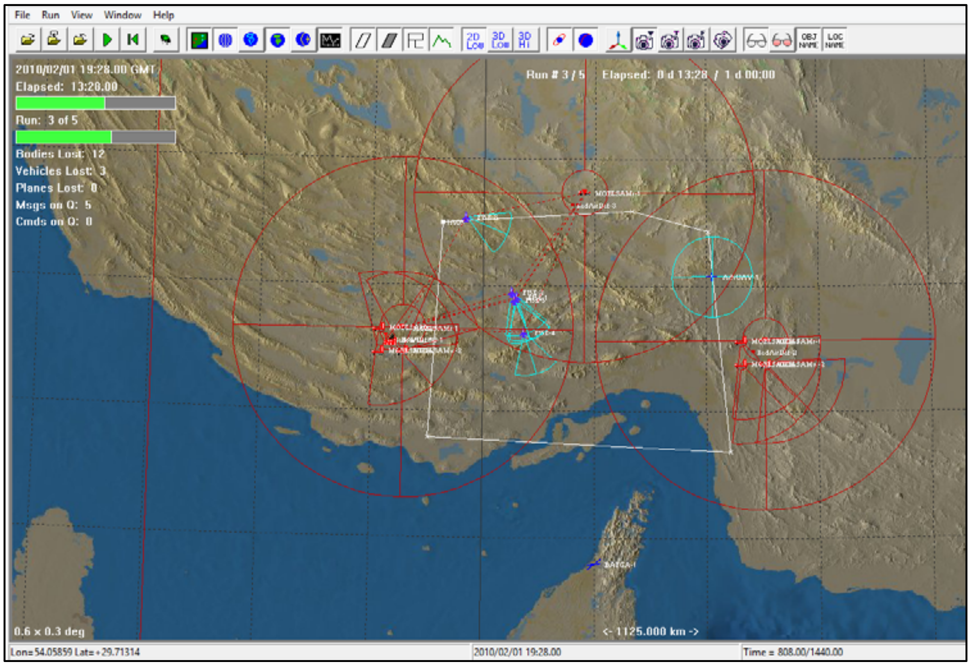


Figure 111. SEAS UI

As shown in Figure 111, the SEAS UI is similar to that of MANA, with the only significant difference being that the model developer cannot make changes to the model directly from this UI. Also, the SEAS UI allows the user to visualize agents at all altitudes, to include space-based agents like satellites or spacecraft. Like JDAFS, any developmental model changes must be made directly in the .war file through the use of the Eclipse IDE. Running the model and setting up multiple replications was also fairly straight forward. For SEAS, I ran each of the two original models 30 times, and the execution time was noticeably fast, though any insight into this should be treated with suspicion because the model used here was far less complex than the other models I investigated.

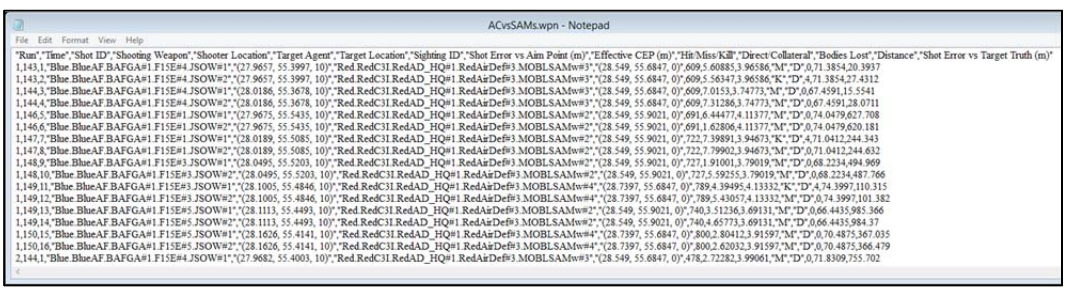
e. DOE

I am fairly concerned regarding the ability of SEAS to support the execution of a large-scale DOE. While SEAS can be used to produce multiple runs of the same design point with different seeds, there is not a readily available tool I can use to execute a large-scale DOE. Even more concerning is that SEAS is not used at NPS, and there is no

resident expertise here that could support the needed development of scripting language to implement SEAS on the computer clusters. Thus, SEAS would likely require a yet undetermined amount of time and money to contract experts to program and implement the needed scripting language, which could potentially induce a whole range of (delay, contracting, cost overrun, oversight) usability issues. It is for these reasons, namely the lack of execution scripts, that I was not able to do execute a full DOE as seen previously.

f. Analysis

As before, the purpose of this section is not focused on analysis per say, but more on how well SEAS supports my research needs. Unfortunately, due to the significant requirements needed to develop a usable SEAS model as well as the scripts needed to execute a DOE, I was unable to achieve many of the analysis demonstrations shown in the MANA section. With this said, I was able to conduct a thorough enough exploration to confirm that SEAS does produce adequate output data for use in my research. While SEAS has a much more robust set of output than most M&S packages, it is not as organized as I would like, and would need some post processing before it can be brought into JMP for analysis. Figure 112 shows just one example of a SEAS output file.


ACvsSAMs.wpn - Notepad
File Edit Format View Help

```
"Run","Time","Shot ID","Shooting Weapon","Shooter Location","Target Agent","Target Location","Sighting ID","Shot Error vs Aim Point (m)","Effective CEP (m)","Hit/Miss/Kill","Direct/Collateral","Bodies Lost","Distance","Shot Error vs Target Truth (m)"
1,143,1,"Blue.BlueAF.BAFGA#1.F15E#4.JSOW#1","(27.9657, 55.3997, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#3","(28.549, 55.6847, 0)",609,5.60885,3.96586,"M","D",0,71.3854,20.3937
1,143,2,"Blue.BlueAF.BAFGA#1.F15E#4.JSOW#2","(27.9657, 55.3997, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#3","(28.549, 55.6847, 0)",609,5.56347,3.96586,"K","D",4,71.3854,27.4312
1,144,3,"Blue.BlueAF.BAFGA#1.F15E#4.JSOW#1","(28.0186, 55.3678, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#3","(28.549, 55.6847, 0)",609,7.0153,3.74773,"M","D",0,67.4591,15.5541
1,144,4,"Blue.BlueAF.BAFGA#1.F15E#4.JSOW#2","(28.0186, 55.3678, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#3","(28.549, 55.6847, 0)",609,7.31286,3.74773,"M","D",0,67.4591,28.0711
1,146,5,"Blue.BlueAF.BAFGA#1.F15E#1.JSOW#1","(27.9675, 55.5435, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",691,6.44477,4.11377,"M","D",0,74.0479,627.708
1,146,6,"Blue.BlueAF.BAFGA#1.F15E#1.JSOW#2","(27.9675, 55.5435, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",691,1.62806,4.11377,"M","D",0,74.0479,620.181
1,147,7,"Blue.BlueAF.BAFGA#1.F15E#1.JSOW#1","(28.0189, 55.5085, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",722,7.39891,3.94673,"K","D",4,71.0412,244.343
1,147,8,"Blue.BlueAF.BAFGA#1.F15E#1.JSOW#2","(28.0189, 55.5085, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",722,7.79902,3.94673,"M","D",0,71.0412,244.632
1,148,9,"Blue.BlueAF.BAFGA#1.F15E#3.JSOW#1","(28.0495, 55.5203, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",727,1.91001,3.79019,"M","D",0,68.2234,494.969
1,148,10,"Blue.BlueAF.BAFGA#1.F15E#3.JSOW#2","(28.0495, 55.5203, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",727,5.59255,3.79019,"M","D",0,68.2234,487.766
1,149,11,"Blue.BlueAF.BAFGA#1.F15E#3.JSOW#1","(28.1005, 55.4846, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#4","(28.7397, 55.6847, 0)",789,4.39495,4.13332,"K","D",4,74.3997,110.315
1,149,12,"Blue.BlueAF.BAFGA#1.F15E#3.JSOW#2","(28.1005, 55.4846, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#4","(28.7397, 55.6847, 0)",789,5.43057,4.13332,"M","D",0,74.3997,101.382
1,149,13,"Blue.BlueAF.BAFGA#1.F15E#5.JSOW#1","(28.1113, 55.4493, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",740,3.51236,3.69131,"M","D",0,66.4435,985.366
1,149,14,"Blue.BlueAF.BAFGA#1.F15E#5.JSOW#2","(28.1113, 55.4493, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#2","(28.549, 55.9021, 0)",740,4.65773,3.69131,"M","D",0,66.4435,984.37
1,150,15,"Blue.BlueAF.BAFGA#1.F15E#5.JSOW#1","(28.1626, 55.4141, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#4","(28.7397, 55.6847, 0)",800,2.80412,3.91597,"M","D",0,70.4875,367.035
1,150,16,"Blue.BlueAF.BAFGA#1.F15E#5.JSOW#2","(28.1626, 55.4141, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#4","(28.7397, 55.6847, 0)",800,2.62032,3.91597,"M","D",0,70.4875,366.479
2,144,1,"Blue.BlueAF.BAFGA#1.F15E#4.JSOW#1","(27.9682, 55.4003, 10)","Red.RedC3I.RedAD_HQ#1.RedAirDef#3.MOBLSAMw#3","(28.549, 55.6847, 0)",478,2.72282,3.99061,"M","D",0,71.8309,755.702
```

Figure 112. SEAS Weapon Output File Format

As shown in Figure 112, this weapons output .csv file contains all the data needed to compute a victim/shooter score card, and thus, it should be possible for SEAS to produce data to the same level of detailed needed for my work. Once the necessary scripts are developed and post processing is complete, analysis of SEAS output should be relatively straightforward.

Although these SEAS models were relatively simple, I was able to verify that SEAS is capable of producing robust enough data with enough depth to allow for valuable analysis in support of my research. As long as the potential issues regarding the development and implementation of the necessary scripts needed to execute a large-scale DOE are addressed, I am more than confident that SEAS can produce the data needed to conduct the level of analysis needed for my work.

g. Findings

Overall, I believe that SEAS is an extremely flexible environment that can be used to meet all of my modeling requirements. Following this investigation, I conducted a qualitative assessment of SEAS' ability to meet each of my primary and secondary research needs, and the scoring of this assessment can be seen in Table 76.

Table 76. SEAS Assessment Table

Weighted Decision Matrix		
Weight	Factors	SEAS
6	Ability to Simulate a D3SOE	5
5	Support Availability	2
5	Cluster Access	2
5	Ease of Use	3
4	Rapid Development	2
4	Existing Models	2
4	Ease of Analysis	3
4	Output Data Density	4
3	Learning Curve	4
3	Behavior Monitoring	3
3	DOE Tools Available	2
2	Ease of DOE Execution	2
	Total Value	140

As shown in Table76, I felt that SEAS was more than capable of modeling the impacts from a D3SOE, as well performing fairly well across the primary considerations for my work. Unfortunately, SEAS did not score as well across the secondary considerations regarding usability, which could impact the overall utility of SEAS when considering my research.

F. M&S COMPARISON AND EVALUATION

With the investigation complete, it was now time to qualitatively compare each of the three potential M&S packages against each other. Specifically, I will be considering how well each of the three M&S packages supports the three primary areas of a D3SOE which I am attempting to model, as well as how each addresses the primary and secondary considerations mention in the first part of this chapter. After doing this comparison, ample qualitative data should be available to justify the selection of an M&S package for use in my work.

1. Comparison

The following comparison is a qualitative assessment of each of the three potential M&S packages' ability to meet the major requirements for my work, as well as their ability to meet specific secondary considerations, when compared to each other. I attempted to do this comparison in the order presented in the previous investigation sections, specifically focusing on the considerations that I thought were the most relevant. The following areas were considered for this comparison.

a. Modeling a D3SOE

When considering how well each M&S package models a D3SOE, I focused on how well each model supported the modeling of the three primary effects which I was trying to represent, specifically, communications, ISR, and PNT degradation. My comparison of each of the three potential M&S packages follows.

(1) Communications Degradation

Like most M&S packages I investigated, there are no direct or specific factor settings for degrading communications, ISR, and GPS in MANA or JDAFS. Luckily, because of the implementation of MANA, there are several factors which can be used to degrade communications. MANA offered many of these knobs, like latency, capacity, reliability, and delay, but JDAFS does not. Because each agent in MANA shares information through links, it is easy to build accurate communications links to represent real world communications, then later degrade these links based on the expected impacts

from adversary jamming. This is not possible in JDAFS because it inaccurately models communications, a consideration that cannot go unnoticed. So, unless I can figure out a way to represent this effect, JDAFS may not be suited for modeling communications.

Unlike MANA, which required the use of surrogate factors to represent impacts to communications, SEAS can do so directly. This is a significant advantage, and allows SEAS to model communication links in great detail, as well as the effects of degradation to communications and adversary counter-space systems and capabilities, something neither MANA nor JDAFS can do. Unfortunately, the flexibility of SEAS to model these aspects comes at a significant cost of development time and resources needed to code in the desired functionality. While MANA is not as capable of modeling communications degradation to the level of detail as SEAS, it does not require any additional resources to achieve a usable model, something that must be considered.

(2) ISR Degradation

Once again, it seems that SEAS is able to model ISR collection assets in far greater detail than either MANA or JDAFS, as well as the ability to model adversary counter-space capabilities and effects that could impact these systems, to include kinetic and non-kinetic weapons. But again, this flexibility requires a significant commitment of resources to code in the desired functionality, something both SEAS and JDAFS must consider. While MANA is not as capable as SEAS in modeling ISR degradation, it requires little effort to achieve a usable model, and it is far more capable than JDAFS, which does not have the capacity to induce lag, inaccuracies, or degradation of collection capabilities. Thus, SEAS is the most capable and should be a user's first choice given adequate time and resources. In any situation where these resources are restricted, MANA quickly becomes more advantageous due to its reduced development requirements. In neither case is JDAFS more advantageous with regard to ISR degradation

(3) PNT Degradation

Like many other M&S packages, there was no direct way to induce the locational degradation I was attempting to model in either MANA or JDAFS. For MANA, there

simply were no factors that could induce positional error or represent location uncertainty by agents. In MANA, once an agent is detected and classified, its location is known without error, and then communicated to other agents over time. In reality this is never the case, and in a D3SOE it is even further from the truth. So unfortunately, agents have perfect SA of all detected agents. This problem is even worse for JDAFS because the SA picture of all agents in JDAFS is known instantly without the need for communications by all friendly forces once it is detected, without error. Thus, agents have perfect SA of all friendly forces as well as everything that is detected. Thus, there is no way to directly induce positional error in JDAFS, nor is there a means in which to affect it through communications links, because there are none. Fortunately, unlike MANA and JDAFS, SEAS is capable of degrading the capabilities of U.S. PNT signals directly, inducing both locational and timing errors to either the satellite or to the terminal users, which is extremely advantageous.

(4) General Comments

In conclusion, it seems that SEAS is by far the most capable of the M&S packages investigated regarding capacity to model a D3SOE. As an Air Force model, SEAS was designed primarily for this purpose, and thus, can directly model all of the effects that I am trying to represent without the use of surrogates as I am required to use to various extents with both MANA and JDAFS. SEAS allows the user to not only model the systems, but the counter-space capabilities, and effects on communications, ISR collection, and PNT degradation as well, directly, without modification or the use of surrogates. Therefore, SEAS has the potential to be far more accurate when compared to other models of equivalent resolution and detail.

MANA on the other hand meets nearly all of my primary and secondary requirements, but does not have the depth of factors seen in SEAS that I would need to model the impacts of a D3SOE on combat effectiveness directly. Fortunately, because MANA provides an extremely robust communications architecture and SA picture, it provides more than enough knobs to turn to represent the impacts from operations in a D3SOE through the use of surrogates. So the lack of fidelity in how MANA models a D3SOE is not a very significant disadvantage, far less significant than the

disadvantageous seen in JDAFS. While JDAFS has enough flexibility to provide some of the factors needed for use in my research, its inability to model communications effectively is a significant concern. When coupled with the unknown resource requirements needed to code in the desired functionality, the overall usability of JDAFS to support my work is significantly undermined.

b. Usability

With respect to my secondary consideration, MANA is extremely user friendly, with an exceptional amount of local support material and expertise here at NPS. MANAs nature as a time step model makes it extremely easy to do incremental development changes and conduct small simulation batch runs to observe the behavior of the model. JDAFS is not nearly as user friendly as MANA, although it does have a fair amount of support material and support expertise locally here at NPS, it is not nearly as robust as what is available for MANA. Although it lacks the elegance of MANA, it is fairly easy to implement and run, with a simple UI that is easy to navigate. What is most notable thus far is that JDAFS does not allow a user to make any changes to the model through the UI; it exists solely to allow a user to run a model. This is vastly different from MANA, which allows changes to the model directly from the UI which significantly reduces the complexity of incremental development. Likewise, SEAS is also not as user friendly as MANA, though it is far better than JDAFS. Like JDAFS, SEAS requires the use of a separate IDE for modification to the model. Thus, we cannot make developmental changes to the model through the UI. While not nearly as user friendly as the MANA UI, which provides a single user friendly UI for model development, test, and evaluation, it is far cleaner and more usable than JDAFS. Although this is relatively insignificant by itself, when coupled with the lack of any local support or expertise here at NPS we find that the overall usability of SEAS is significantly degraded.

c. Flexibility

MANA is a proprietary software suite made available for use at NPS. Thus, the functionality of the software is limited by its development and source code, and cannot be expanded or changed to account for new concepts without support from the developer.

Thus, MANA is only as flexible as its design, and while its design is fairly flexible and can account for most user needs through a broad set of factors, it cannot account for everything. Thus, my ability to use MANA to model the entire range of a D3SOE is limited. So, while MANA is easy to use, highly capable, with little to no developmental requirements, it cannot get any better than it already is. SEAS and JDAFS on the other hand have the potential to be far better at modeling a D3SOE.

Because of the inherent flexibility of both SEAS and JDAFS, stemming from their status as a simulation frameworks, and ability for growth of both is far superior to most commercially available M&S packages, to include MANA. Thus, because the source code is free and open, and does not require the owner to implement changes, both SEAS and JDAFS are expandable, and can account for behaviors that MANA cannot. This allows the developer to add in any functionality they may require. This is extremely advantageous when considering the modeling of a D3SOE as in my research, because this functionality does not currently exist in most M&S packages.

Unfortunately, this flexibility comes with the significant cost of time and resources in order to code in the needed functionality. Neither SEAS nor JDAFS start with any functionality, so while they have the potential to provide a more in-depth and detailed accounting for a D3SOE than MANA, a significant investment of time and resources would be needed in model development in order to code the needed functionality. While this disadvantage could be mitigated by the re-use of existing models that had the functionality I was interested in, neither SEAS or JDAFS had any available at the level of complexity I need. Because I do not have the time or resources needed to execute this development, I do not believe that SEAS or JDAFS are feasible for my needs. And even though MANA has the potential to be less accurate than SEAS or JDAFS, it is usable now, without development delays. Couple this with the fact that MANA is fairly capable, though not as capable as SEAS, and it is easy to justify the advantage of MANA over both SEAS and JDAFS.

d. Support

When it comes to support, MANA is by far the best M&S package available for use in my work. MANA has been extensively used in research at NPS, especially in the OR department, where it has been used as the primary M&S package in over twenty thesis and at least three dissertations. This has two significant advantages. First, it provides a large pool of past work from which I can uses as a foundation for my own work. Second, it provides a large pool of experts which I can contact for support when needed. By having resident experts in MANA here at NPS, any issues encountered during model development can be overcome, something neither JDAFS nor SEAS can claim.

While JDAFS does have some support at NPS, it is just a single person, and not nearly as robust as what is available for MANA. This is further complicated by the fact that there has been little past work done using JDAFS, and thus, there are few models in which I can leverage for my own work. The support available for SEAS is even more restricted due to the complete lack of any resident expertise at NPS. Thus, the use of SEAS would likely require the contracting of outside support to achieve a usable model. Coupled with the fact that almost all models using SEAS are classified, and we again find a situation where there is little past work in which I can leverage for my own work. Thus, like JDAFS, SEAS is at a significant disadvantage when compared to MANA when considering the availability of support.

e. DOE

Because the production of meta-models is a primary consideration for my work, the use of a large-scale DOE must be considered when conducting this assessment. While all three M&S packages were capable of executing of producing multiple runs of the same design point with different random number seeds, not all were as capable of being executed in conjunction with large-scale DOEs. Without the ability to rapidly develop and execute a large scale DOE it will be difficult to get enough output data for adequate analysis, and thus a consideration when selecting an appropriate M&S package.

MANA is by far the simplest M&S package to use in conjunction with a large-scale DOE. Since MANA is used extensively at NPS, especially in the OR department,

there resides a host of support for MANA, to include pre-existing scripting to enable rapid model execution of large-scale DOEs. For example, using the NPS computer clusters, I was able to run a fairly complex MANA model in a 25700 design point NOLH design in less than a day. The availability and rapid turnaround of the MANA compatible computer cluster is a significant advantage of MANA over both SEAS and JDAFS, because the same level of support may not be available for other M&S packages.

The lack of any historical use or expertise of SEAS at NPS has resulted in a situation where the required execution scripts currently do not exist. Thus, a significant amount of effort would need to be dedicated to the scripting and integration coding required to execute a SEAS model on the NPS cluster. And since it has never been done before, there is a lot of uncertainty regarding the ease in which this could be accomplished. JDAFS on the other hand does have some execution scripts available, but have not been used in many years and would need a fairly significant update to become viable for my use. Thus, another significant chunk of time and effort to be dedicated to the scripting and integration coding required executing either SEAS or JDAFS on the NPS cluster. This is a significant disadvantage when compared to the easy of a DOE using MANA, and could significantly degrade the usability of SEAS or JDAFS.

f. Analysis

Because MANA and SEAS are both combat models, their outputs naturally include a host of relevant combat statistics to include force losses, losses by source, as well as killer-shooter information that is critical for good analysis. Thus, it is easy to generate measures of combat effectiveness for comparison, such as FER, LER, and LoB with either MANA of SEAS. While SEAS seems to have a much more robust set of outputs than MANA, specifically regarding space and communications specific information, it is not nearly as well organized, and like JDAFS, will require some post processing before it can used in analysis. Regardless, it seems MANA and SEAS are both well equipped to provide adequate output data needed to conduct higher level analysis and modeling of responses.

JDAFS on the other hand was originally designed as an optimization tool, and thus, does not provide output data nearly as organized as either MANA or SEAS. Though everything that is needed to conduct further analysis is present, it will require a fair amount of post processing to prepare it for further analysis. One advantage of JDAFS over both MANA and SEAS is the fact that it is a DE model, and thus, it will not suffer from the same artifacts and anomalies that time-step models suffer from. While time-step models have many advantages, the one overarching disadvantage is that they suffer from induced error caused by the selection of the time-step size. Because JDAFS is a DE model, which executes events as they occur, it avoids inducing this type of error, and thus, has the potential to be far more accurate when compared to both MANA and SEAS.

g. Agent Behavior

The primary concern regarding agent behaviors resolve around two primary topics, which include accuracy of the combat model, how well a model represent ground combat operations, a primary consideration; and autonomy, how agents execute decision making and movement on the battlefield. Let us start with combat operations.

Because MANA is a ground combat model, it does a fairly good job at modeling combat operations. Although it does not model the space element in any way, as SEAS does, it is possible to represent the effects of space. SEAS on the other hand does not model ground combat operations to the same resolution or accuracy as it does the Air and Space component. Therefore, it is difficult to validate the performance and accuracy of ground combat in SEAS because not only is the accuracy of the ground segment suspect, but the Air Force centric measures of combat effectiveness used by SEAS do not translate well to Army metrics of combat effectiveness. JDAFS on the other hand, while more combat oriented than SEAS, is also restricted in its capabilities to its implementation as an optimization tool. And although it is more accurate, its range of usability is much reduced when compared to either SEAS or MANA.

With regard to autonomy, MANA is the only truly semi-autonomous agent-based simulation I investigated. Because neither SEAS nor JDAFS possess any agent personality attributes that are used by the agents to make operational decisions, agents in

SEAS and JDAFS are not nearly as autonomous as agents in MANA. Thus, these agents require more directed and scripted orders from higher elements to execute decision making. The inability of agents to act semi-autonomously significantly reduces the power of the simulation to address emergent behaviors, as well as increasing the amount of hierarchical structure required to represent the BMC2 aspects of the simulation.

The largest impact this has on a simulation is that almost all maneuver in SEAS and JDAFS is scripted, and thus difficult to model the fluidity of how actual ground maneuver develops and transforms as the COP is developed. This is possible in MANA because agent decisions are based on a set of attributes that can be used to determine its actions. Thus, MANA does not require a script for its agents to follow as does SEAS and JDAFS, which use a simple set of movement rules and a list of waypoints to execute movement. Thus, Blue forces in JDAFS and SEAS will go wherever the highest value target is, regardless of the efficiency of the move or the location of friendly forces or other objectives. This lacks in almost every way when compared to MANA in representing actual combat maneuver. For example, there is no associated value to maintaining unit cohesion, or mass, when moving in either JDAFS or SEAS without scripting. The inability of JDAFS and SEAS agents to model these standard principles of military tactics is a significant drawback.

Another significant disadvantage of JDAFS regarding movement is that it does not account for terrain or Line of Site (LOS) calculations during movement. This was by design, and due to the fact that JDAFS was originally developed to model the allocation of fires and sensors, both typically considered Non-LOS systems, and thus, not impacted by intervening terrain or LOS restrictions. But because I am attempting to use this model in support of ground combat operations, JDAFS inability to model the impacts from terrain is a significant disadvantage.

2. Evaluation

With the investigation and comparison complete, I decided to do a weighted decision support matrix to attempt to quantify how the three potential M&S packages met my primary and secondary requirements for my research. While this is highly qualitative,

because I compared each potential M&S package against each other, as well as assessing the ability of each to meet both primary secondary usability considerations, I am confident that it is more than appropriate for this purpose. Table 77 shows the weighted decision matrix I used to conduct my comparison, where I weighted each factor by its expected impact and importance to meeting my research objectives.

Table 77. Decision Matrix

Weighted Decision Matrix				
Weight	Factors	MANA	JDAFS	SEAS
6	Ability to Simulate a D3SOE	3	2	5
5	Support Availability	5	4	2
5	Cluster Access	5	4	2
5	Ease of Use	5	2	3
4	Rapid Development	4	2	2
4	Existing Models	5	2	2
4	Ease of Analysis	4	3	3
4	Output Data Density	4	3	4
3	Learning Curve	4	2	4
3	Behavior Monitoring	4	2	3
3	DOE Tools Available	5	3	2
2	Ease of DOE Execution	5	2	2
	Total Value	210	127	140

As shown in Table 77, my qualitative assessment recommends the use of MANA for my dissertation research. MANA dominates the other two M&S packages, scoring 70 points higher than the SEAS, the next best package. While SEAS is by far the most capable of modeling a D3SOE, its lack of available models and uncertainty regarding the modeling of ground combat makes its use questionable at best. Couple this with the fact that MANA beats or ties SEAS in every other area considered, many of which dealt with model usability in context of my research, and it is easy to justify the selection of MANA over SEAS and JDAFS. Therefore, based on this analysis, I will be using MANA as my M&S package for this research.

G. CONCLUSION

The purpose of this chapter was to address the first of the supporting research questions as outlined in Chapter I, specifically, to identify what M&S packages where available that could accurately model the effects of a D3SOE on combat operations. In this Chapter I identified 14 potential M&S packages that after initial inspection seemed

as potential candidates for use in my work. After conducting a more thoughtful and detailed investigation of these alternative M&S packages, using primary and secondary screening considerations, I was able to reduce this list from 14 to just three. Following this, I conducted a detailed exploration of each of these three M&S packages to assess the appropriateness of each M&S package for use in my work, providing a solid foundation of analysis to justify the selection of MANA as the M&S tool for use in my research.

APPENDIX B. SPACE THREATS AND DEPENDENCIES

At no prior point in the history of the U.S. Army have force multipliers like space-based capabilities been so heavily leveraged to mitigate operational risk. The Army uses its access to advanced space-based technologies and capabilities to secure and widen the tactical advantage over its adversaries in order to overpower and defeat them. By leveraging these advantages, the Army is able to maintain a smaller, more agile force that is capable of fighting and winning in a complex world, often in situations where it is out-manned, out-gunned, and out-resourced. Yet, Army requirements are expected to grow even in the midst of a significant reduction in force structure, and as the proverbial saying goes, the Army is now expected to "*do more with less*." As outlined throughout the new AOC (U.S. Army 2014b), the future force will need to be smaller, lighter, more agile, more deployable, more capable, have a smaller footprint, have reduced support and sustainment requirements, and rely more on reach back support and capabilities, all the while maximizing its combat effectiveness to achieve overmatch with less. But this proverbial tightening of the belt does not come without risk.

A. U.S. SPACE DEPENDENCIES

Today, the space domain is truly a global commons, the ultimate high ground from which state and non-state actors alike will leverage to meet their own ends. While this realization is evident in U.S. national policy, the DOD has been slow to adapt to the change in the OE. While the United States overall market share of operational satellites has been falling over the last 10 years as more and more countries expand into the space domain, the United States remains heavily invested in the advantages that space affords both militarily as well as commercially. A summary of the current operational satellites can be seen in Table 78.

Table 78. Satellite Quick Facts through August 31 2015.
Source: Union of Concerned Scientists (2015).

Total number of operating satellites: 1,305			
United States: 549	Russia: 131	China: 142	Other: 483
LEO: 696	MEO: 87	Elliptical: 41	GEO: 481
Total number of U.S. satellites: 549			
Civil: 21	Commercial: 250	Government: 126	Military: 152

As shown in Table 78, even using the simplest of metrics, the United States is four times more invested in space than what many would consider our near-peer competitors. While this may or may not denote a U.S. dependency, it is easy to see how it could be interpreted as one. Even when considering just the 278 military/government satellites, a fairly conservative estimate, we see that they account for more than the total number of satellites operated by both China and Russia combined (273). Thus, from a purely quantitative perspective, U.S. Militarily relevant space assets account for over 20% of all operating satellites worldwide; this is a huge percentage when considering the breadth of all space-based activities worldwide. Table 79 shows a consolidated table of the five Space Force Enhancement Mission Areas and their associate uses with regard to the six Army Warfighting Functions. This table was created to capture warfighter space dependencies, and while it is not all inclusive, it gives some needed detail on how the Army depends on space-based capabilities to support combat operations.

Table 79. Space to Warfighting Function Crosswalk.
Source: DOA (2014, 3–20).

	Mission Command	Movement and Maneuver	Intelligence[1]	Fires	Sustainment	Protection
Space Force Enhancement Mission Area						
ISR	• Geospatial Info • Situational awareness • Imagery • Terrain	• Geospatial Info • Situational awareness • Imagery • Terrain	• Geospatial, measures, and signal intelligence • Terrain	• Battle damage assessment • Terrain	Not applicable	• Geospatial Info • Situational awareness Imagery • Terrain
Missile Warning	• Missile launch and impact • Ballistic missile warning	• Predicted Impact points	• OPIR • Operational area awareness	• Missile launch cueing	Not applicable	• Predicted impact • Ballistic missile warning
Environmental Monitoring	• Weather	• Operational planning • Imagery • Mobility	• Weather	• Operational planning • Imagery • Mobility	• Operational planning	Not applicable
SATCOM	• BLOS comms • NLOS comms • Reachback	• BLOS comms • NLOS comms	• Reachback • Reach forward	• BLOS comms • NLOS comms	• BLOS comms • NLOS comms	• BLOS comms • NLOS comms
Position, navigation, and timing	• FFT • JBCP with FFT • Critical timing	• FFT • JBCP with FFT • Position, navigation, and timing	• FFT • JBCP with FFT	• Precision targeting • NLOS Fires • JBCP with FFT	• FFT • JBCP with FFT • In-transit Visibility	• FFT • JBCP with FFT

1. Space operations enable certain capabilities within the Intelligence warfighting function operations, but Space operations are also dependent upon Army Intelligence to provide reconnaissance, surveillance, and intelligence products and information.

BLOS – beyond line of sight; FFT – friendly force tracking; JBCP – joint battle command platform; NLOS – non-line of sight; OPIR – overhead persistent infrared; SATCOM – satellite communications; ISR – intelligence, surveillance, and reconnaissance

As shown in Table 79, each of the Warfighting Functions listed across the top are saturated with dependencies from the Space Force Enhancement Areas listed on the side. To provide more detail regarding the contributions of the Space Force Enhancement Mission Areas to the Warfighting Functions, a brief description is provided:

- The Mission Command function requires space capabilities to support SA and command and control.
- The Movement and Maneuver function requires space capabilities to support planning and decision making for current and future operations.
- The Intelligence function uses space capabilities to support building a more accurate assessment of the enemy and the OE.
- The Fires function relies on space for targeting, information sharing, and precision fires.

- The Sustainment function uses space capabilities to support the speed and efficiency of logistical operations in support of combat, specifically friendly force tracking and communications.
- The Protection function relies on space-based capabilities to provide SA of friendly and adversary forces, as well as early warning of impending attacks in order to give U.S. forces time to protect soldiers and systems.

Each of these space force enhancement areas supports U.S. operations in one form or another. “Satellite communication (SATCOM) allows forces to operate over extended ranges; the Global Positioning System (GPS) delivers precise positioning, navigation, and timing; and space-based Intelligence, Surveillance, and Reconnaissance (ISR) systems provide unprecedented situational awareness of adversaries” (U.S. Army 2014a, 1). These three areas, plus missile warning and environmental monitoring will now be discussed in more detail.

1. SATCOM

Speed of communication as well as the quality and accuracy of information has always been a crucial factor in determining the outcomes of conflict. Today, this fact holds true, and SATCOM is the most operationally relevant space-based capability utilized by the DOD. By providing warfighters with “a global network of joint military and commercial communication satellites, operating forces at all levels of command to overcome limited infrastructure, execute reachback operations, enable two-way flow of data to critical nodes, provide support to special users, and increase overall command and control effectiveness” (DOA 2014, 3–10). Fundamentally, all space-based capabilities and services provided to the warfighter depend on communications. ISR, MW, PNT, and all other space-based capabilities utilize communications to deliver their services to the users, thus, SATCOM communications is the central cog in the Army’s informational war machine. Communications, specifically the ability to rapidly communicate information anywhere at any time, is the key driver of U.S. Military tactical advantage. In its simplest form, it is focused on providing users a better understanding of the OE, and in turn, allows leaders to make better and faster decisions, enabling the military to “out decide” its adversaries and gain tactical advantage. The ability to rapidly disseminate information, SA, and BMC2, gives the U.S. Army an unparalleled ability to quickly

execute the decision making cycle -- a significant advantage over adversaries who require more time to gather, process, and disseminate the information needed to make decisions. Without SATCOM, the USGs ability to achieve and maintain overmatch will be significantly hampered, leaving the Army unable to provide many of the key space enabling technologies to the forces who can best exploit them. Generally, SATCOM can be broken down into four primary types.

a. Narrowband SATCOM: UHF

The U.S. military uses Narrowband SATCOM systems primarily in support of tactical operations, which provides highly mobile forces with easy to use, small, and light weight voice and data communication systems. Narrow band systems like UFO and MUOS "support secure voice and data transmission at relatively low data rates for mobile and fixed users" (DOA 2014, 3–12). The Army depends on narrowband SATCOM in environments where no infrastructure exists to support larger and higher capacity systems, like we expect to see in the future. Thus, according to the new AOC, the Army is expected to leverage these types of communication systems even more as the Army transitions into a more expeditionary force. Unfortunately, due to the spectrum characteristics that make systems operating at this band useful to tactical users – such as low power, small size, and rapidly deployable -- systems at this frequency band are fairly vulnerable to adversary counter-space activities.

Narrowband systems are extremely susceptible to nuclear scintillation and EMP, jamming, interference, as well as the space environment. Thus, operations in this band are significantly more risky than at higher bands. Additionally, because of the limit width of the band (from 0.3 to 3 GHz) as well as the large number of users, it is a crowded spectrum, and often subject to prioritization of bandwidth. Luckily, the relatively low data rate of the systems, the number of transponders available, the use of spot beams, and the U.S. military's ability to dynamically re-allocate bandwidth mitigates the risk somewhat. Adversaries will be forced to weigh the cost of attacking these systems with the expected operational impacts. Those who choose to use counter-space capabilities will need to do so purposefully and will need significant resources of intelligence, time,

and continuous monitoring to accurately select the frequencies/transponders that they believe to be the most critical to U.S. operations.

b. Wideband SATCOM: SHF/EHF

The U.S. uses Wideband SATCOM systems in support of the operational level of military operations, primarily at the BDE and above level. These semi-mobile elements are less constrained by power, weight, and size limitations and require significantly more information and data capacity to conduct effective operations compared to the lower level tactical elements. Wideband SATCOM provides more capacity for users than Narrowband through greater bandwidth and additional channels, as well as "multichannel, secure voice, and high rate data communications for mission command, crisis management, and intelligence data transfer services" (DOA 2014, 3–12). The Army depends on Wideband SATCOM to provide the majority of its data requirements at the tactical and operational levels of war. As the informational demands of the warfighter continued to increase, the inability of existing systems to meet the need drove the development of high capacity communications systems. These systems, like DSCS and WGS, comprise the majority of the military communications architecture. Unfortunately, while these systems are less vulnerable to nuclear scintillation and have greater imbedded protection measures, they are still fairly susceptible to adversary counter-space activities.

Wideband satellites provide the majority of voice and data requirements for operational warfighters when compared to both Narrowband and Protected SATCOM. Couple this dependency with the relatively small number of military Wideband systems, and the risk is even more pronounced, presenting a potentially lucrative target set for adversary counter-space capabilities. Fortunately these risks are mitigated in a few ways: the orbits of the systems; the width of the band (from 3 to 30 GHz); the use of spot beams; advanced modulation schemes; and dynamic frequency allocation. The combination of Wideband SATCOMs significance to U.S. operations and its expected vulnerabilities would likely draw significant attention from adversaries. Adversaries have the capability to limit the effectiveness of these systems, and while Protected and

Commercial SATCOM systems could be utilized to mitigate this capability loss, the timing, saturation, and persistence of an attack could steal the initiative from U.S. forces.

c. *Protected SATCOM: Narrow beam/spread spectrum SHF/EHF*

The U.S. uses Protected SATCOM systems in support of the operational and strategic levels of operations, primarily at the senior command level of military and government. These elements and organizations typically occupy fixed sites, with few limitations on power, weight, or size, and require some level of assured voice and data communications. Protected communications are typically reserved for the most vital requirements of the USG, that typically require “survivable voice and data communications not normally found on other systems” (DOA 2014, 3–12). Through the combination of modulation and protection schemes, protected communications are resistant to scintillation, interference, and jamming. While lacking the capacity and throughput of Wideband systems, Protected SATCOM provides users assured communication of the most critical national and strategic information. These systems, like MILSTAR and Advanced EHF comprise the backbone of the military communications architecture, where the majority of all strategic BMC2 is conducted.

Unfortunately, while these systems are extremely difficult to attack, being nearly invulnerable to nuclear scintillation or jamming, they are still susceptible to adversary kinetic counter-space capabilities. While this risk is somewhat mitigated by the orbits of the systems, the combination of Protected SATCOMs’ significance to U.S. operations and their limited number will likely make them a top priority target for adversary kinetic anti-satellite weapons. While Wideband and Commercial SATCOM systems could be utilized to mitigate this capability loss, attacks against protected systems would have detrimental and cascading effects on U.S. operations at the strategic level. Without its eyes and ears, the U.S. may not have a full understanding of the OE, and thus may inadvertently make decisions that could significantly increase the chances of conflict escalation. Therefore, rational adversaries would likely give some strategic pause before attacking these systems, as Wideband satellites would likely have far more tactical relevance in a regional conflict without risking the chance of conflict escalation.

d. Commercial SATCOM

The military needs information in order to drive its operational battle rhythm. The speed, quantity, and quality of information directly impacts the pace and outcome of battle, and gives the U.S. a tactical advantage when its use is maximized in coordination with operations. Recognizing this, military forces have developed an insatiable appetite for more and more information, yet this need for information has far outpaced the USs ability to provide it. This has forced the government to outsource much of its steady-state communications requirements to commercial SATCOM providers, who can offer "greater capacity that can be exploited to meet and augment the Army's rapidly growing information needs" (DOA 2014, 3–13). Recent reports suggest that over 80% of the military's steady state Wideband STACOM requirements are currently being met through the leasing of commercial bandwidth. While there are some potential security risks with this, the benefits are significant when considering adversary counter-space capabilities.

Mitigating the potential impacts to combat effectiveness of U.S. forces can be achieved in a few ways. First, there are a lot of commercial SATCOM providers, and attacking one, or even a few, would not likely have a large enough impact to the opposing force to justify the effort. Second, commercial SATCOM systems are not government satellites, so they are not technically military targets, so there would be some international law and policy factors to consider. Thirdly, commercial SATCOM providers support numerous countries and clients, and an attack on a SATCOM system will likely impact many other countries than just the one targeted. This is likely counterproductive to the aims of the adversary, who will likely want to keep the conflict small and more manageable. Thus, U.S. leveraging of commercial SATCOM presents adversaries with a relatively difficult problem to solve.

2. ISR

The U.S. Army is a consummate consumer of ISR. As an organization that executes current and future planning cycles continuously, the Army has a high demand for current and relatively high resolution Electro Optical (EO), Infrared (IR), and radar imagery in support of planning. While ISR can be collected from numerous sources,

including Air, UAV, High altitude, Near Space, and Space, space-based platforms are the only dependable and routinely available source of high resolution imaging, and are “a crucial enabler supporting all Army operations” (DOA 2014, 3–6), providing the U.S. nearly unrestricted access to denied areas. The information provided by ISR is often critical to decision making, and “supports the development of intelligence that supports mission success, and other actions that may influence the commander’s current and future operational decisions” (DOA 2014, 3–6). Without ISR, the USGs ability to maintain up to date SA regarding adversary force distribution, disposition, strength, and location will be severely compromised. This will force commanders to slow the pace of battle as they seek other less efficient means to fill the informational gaps left by the loss of ISR. Thus, the rate in which the Army can execute its decision making cycle is slowed, reducing its operational overmatch and giving the adversary more time and space on the battlefield.

The greatest risk to collection assets is to the high resolution U.S. space-based ISR assets because of there are a relatively small number of them. Couple this fact with a high demand signal for the capabilities, and one can quickly see how adversary actions against even a single system can have significant impacts on operational effectiveness. The relatively low mission altitudes and advanced capabilities of these systems leave them extremely vulnerable to attacks, especially from laser and kinetic attacks. Thus, a relatively small adversarial investment into counter-space capabilities like lasers, focused on temporarily blinding U.S. ISR assets, has the potential for a huge return on investment, making them attractive options for future adversary R&D programs. While the risk from laser dazzling attacks are high, they are relatively short lived and their long term impacts to operations are low to moderate depending on the timing of the attack. On the other hand, while the risks from kinetic attacks are lower, the impacts are far more significant. Not only do successful kinetic attacks destroy target satellites, they have the potential of creating massive debris fields that can significantly hamper other satellite operations and possibly even destroy them.

Luckily the laser and kinetic threats are mitigated in a few ways. First, only three countries -- Russia, China, and the U.S. -- have demonstrated the capability to conduct kinetic attacks on space systems’, thus there is a relatively small number of these

weapons. Second, the destruction of a U.S. satellite could be considered an act of war, and thus, it is a red line that would give most adversaries pause before executing. Lastly, by using commercial imagery to supplement U.S. collection shortfalls, which currently provides greater than 50% of Army imaging requirements, the United States has disaggregated its “eggs” to other baskets, giving adversaries a larger number of potential targets that make it more difficult to effectively degrade U.S. collection capability.

3. PNT

The ability to provide the warfighter at all levels of operations with detailed position and timing data, anywhere in the world, has given the U.S. military a significantly better understanding of the OE. The Army depends on GPS to support offensive and defensive operations, which are “enabled through precision navigation aids and through networked mission command, control, and communications capabilities that depend on timing signals from the GPS transmission” (DOA 2014, 3–15). The Army uses GPS to reduce uncertainty, both in adversary as well as friendly activities. More accurate location accuracy leads to more accurate SA, more effective maneuver, and more accurate targeting. More accurate timing data leads to more efficient and effective networks and communications. This allows decision makers to more accurately assess operations, the threat, and the environment, and allows them to make quicker and better informed decisions, which can drastically increase the operational tempo of the Army. This increased pace of battle gives the Army a tactical advantage over adversaries who are unable to execute their decision making cycle as quickly. Thus, it is easy to see how the loss of PNT can significantly impact the Army’s ability to execute operations effectively. Any degradation to PNT will induce uncertainty into the forces SA, and thus, give decision makers pause as they access the risk of that uncertainty.

Without GPS, the USGs ability to achieve and maintain operational overmatch could be significantly hampered, especially at the tactical level where the advantages of GPS are concentrated in order to generate RCP over opposing forces. Loss or even degradation of the GPS signal will induce some level of uncertainty into the decision making process, which will inevitably lead to a slower decision making process, and thus, a slower pace of battle. Typically, this will favor the defense, and thus, will likely be

detrimental to U.S. operations, that rely on a high operational tempo to achieve operational overmatch by overwhelming adversaries quickly. The U.S. is not designed or optimized to execute slow or prolonged operations, and any impact that causes a decrease in operation tempo will have a corresponding impact on combat effectiveness, likely seen as a higher number of casualties, and increased length of battle. Luckily, the threat to GPS is a fairly localized problem when considering combat operations, where the threat is aimed more towards impacting users than the system themselves.

Mitigating the risk to U.S. combat effectiveness due to adversary actions targeting GPS can and are achieved in a few ways. First, the risk is somewhat mitigated by the orbits of the systems themselves, because the altitude of MEO poses a significant targeting problem for both kinetic and non-kinetic weapons. Second, there are a large number of GPS satellites, and attacking one, or even a few, would not likely have a large enough impact to the opposing force to justify the effort. Third, GPS satellites are now considered civil satellites, and fall in to a "gray area" when considering targeting, so there would be some international law and treaty factors to consider. Forth, GPS is primarily a civil service, providing services to users worldwide, and an attack on a GPS satellite would likely impact many other countries and users, and cause an international uproar, which is likely counterproductive to the aims of the adversary. Lastly, the U.S. is reducing its dependency on GPS alone, and increasing its use of other PNT systems like GLONASS, Galileo, IRNSS, and BeiDou. Because of these factors, it is unlikely that an adversary would attack a GPS satellite. More likely, adversary forces would seek to attack local military users of the GPS signal through the use of local jammers to deny and degrade U.S. positional knowledge at a tactical level. As a result, the adversary could achieve many of the same objectives as attacking many GPS satellites, at least locally, but without the difficulty or political backlash of attacking a space-based system.

4. Environmental Monitoring

Environmental monitoring is a fairly broad space mission area that accounts for roughly 20% of the U.S. governments overall earth observation activities and incorporates everything from SAR, disaster relief, weather monitoring, and scientific earth sensing missions. Of these, weather monitoring is the most significant when

considering combat operations, especially when considering the impacts that weather can have on operational measures of effectiveness. Consequently, weather forecasting is an important step in the intelligence preparation of the battle field prior to mission execution. During this step, two types of weather must be considered with respect to their potential operational impacts. The first is terrestrial weather, where by the analysis of "weather data, identifying potential weather effects, and assessing the impact of weather on systems, tactics, and operations provide vital information for commanders to optimally employ their forces" (DOA 2014, 5–3). The second is space weather, which analyzes the effects of solar activity and its impacts on the function and performance of space-based systems. Space weather is unpredictable in both occurrence and scale -- thus, "space weather events may adversely affect PNT, surveillance and reconnaissance missions, as well as terrestrial- and space-based SATCOM capabilities" (DOA 2014, 3–7). This is a relatively new area which has grown in importance as our dependencies on space have increased, driving a need to monitor the space environment in order to anticipate, mitigate, and recover from the impacts of the space environment. While space systems are designed to withstand the space environment, our ability to monitor, understand, and anticipate space weather events is relatively limited, and thus, while the risk is low, the overall impact can be significant.

Like missile warning, the overall risk to environmental monitoring systems from adversary counter-space capabilities is fairly low. This is due to the relatively benign and passive nature of these systems, the large number of them, and the relatively open and free access to the information they provide. Most environmental monitoring systems share their information through a worldwide partnership in which the USG participates. This means that USG environmental monitoring systems provide data to all nations, and vice versa, we have access to every other participating country's data. Thus, attacks against environmental monitoring systems are fairly meaningless, and makes "them relatively low-payoff targets with a significant degree of political risk for the attacker" (Heginbotham et al. 2015, 254). When considering the relatively small number of counter-space weapons capable of affecting these systems, as well as the relatively low payoff for doing so, it becomes clear that it is unlikely that these systems will ever be

attacked. Because of this, as well as the relatively small percentage of environmental monitoring systems when compared to the overall number of U.S. satellites, just 4%, they will not be addressed in detail in this dissertation.

5. Missile Warning

Missile warning accounts for roughly 6% of the U.S. governments' overall earth observation activities. While not a mission area which I will address in detail during this dissertation, space-based missile warning does play an important role in combat operations. Specifically, space-based missile warning has two primary contributions to the overall combat effectiveness of supported forces. First, it provides vital and timely information on adversary ballistic missile launches into the Joint Integrated Air Defense network much earlier than terrestrial systems, queuing positioned air defense assets and providing the detailed information needed to execute intercepts. Second, it provides key information to ground forces on potential target areas minutes ahead of the expected impact, giving ground forces the time needed to execute protection measures to minimize damage and casualties. Thus, space-based missile warning plays a key role in force protection by providing commanders with "early warning of enemy ballistic missile launches via the TES reporting" (DOA 2014, 3–9). In fact, the space-based missile warning network is the United States' primary strategic early warning system for detecting ICBM launches, an essential enabler of U.S. national security.

Luckily, the overall risk to these systems from adversary counter-space capabilities is fairly low because of three key mitigation factors. First, the U.S. has inferred in statements and in policy that any attack on this network could be perceived as a precursor to nuclear attack and that the USG would consider first use of nuclear weapons as a potential response. This strategic message draws a clear red line that would give most rational adversaries pause before crossing it. Second, the majority of these systems are located in GEO and HEO, and by nature of these extremely high orbits makes it difficult to attack them, with only a few adversaries even capable of doing so. Lastly, the overall impact to combat operations for the U.S. is fairly low when compared to other systems like SATCOM and ISR. Together, "these characteristics would complicate Chinese efforts to dazzle, or blind, the system with lasers, thereby reducing

the risk of attack" (Heginbotham et al. 2015, 256). Thus, adversaries are not likely to waste limited counter-space assets on these systems when there are higher payoff targets available, even though the U.S. has relatively few of these systems.

B. THE THREAT

If history has taught us anything it is the fact the humans have never developed a weapon and not used it. Our own doctrine states that "Instead of attacking enemy strength, the goal is the application of our strength against selected enemy weakness in order to maximize *advantage"* (U.S. Marine Corps 1997, 37), so why would we not expect the adversary to do the same? As a result, knowing your adversary and their potential capabilities becomes critical to understanding the risk. Likewise, without an understanding of our own vulnerabilities, it would be difficult to assess how an adversary might attack, and how that attack could affect us. It is now more important than ever to maintain an accurate assessment of adversary counter-space capabilities as well as U.S. vulnerabilities in order to accurately assess and prepare for the inevitability of operations in a D3SOE. As Tellis (2014) states, "Chinese strategists are by necessity drawn to the idea of attempting to neutralize American space capabilities. This lure becomes all the more tantalizing because not only is U.S. space superiority critical for the success of American military operations but its space architecture is as a rule remarkably vulnerable to offensive actions undertaken by an adversary" (4). Thus, the Chinese will likely seek to target these vulnerabilities, by expanding efforts to exploit out perceived weaknesses.

This growth is best demonstrated by the Chinese, who's development of counter-space weapons has mostly gone un-checked over the last 15 years as the United States focused on its Wars in the middle-east, and because of this, China was able to rapidly build and field an impressive array of counter-space capabilities that currently surpass any other country in the world. The Chinese recognized their friction with the United States, which has been highlighted in recent documents which admit that "Chinese defense planners are deeply consumed by the necessity of preparing for an armed confrontation with the United States, which they clearly recognize as a superior military power" (Tellis 2014, 3). China sees conflict with the U.S. as an inevitable part of their

destiny, and have been preparing for it for years. Most PLA literature focuses on this inevitability, and highlights the importance of "destroying, damaging, and interfering with the enemy's reconnaissance ... and communications satellites" when considering conflict with the United States (DOD 2014a, 32). Yet recognizing the advantage of attacking U.S. satellites and having the capability to do so is one thing, but having the willingness is another. Unfortunately, based on additional PRC writings, it seems that the PRC is willing and able here as well, stating that "prosecuting counterspace operations in a crisis may be rational for China in any significant Sino-U.S. conflict along its periphery, even though Beijing itself stands to lose considerably as a result of the expected American riposte" (Tellis 2014, 3).

To give some context regarding the potential threat, I have provided some additional insight to a list of major Chinese counter-space development activities mentioned in the testimony of Ashley J. Tellis (2014).

- Direct-Ascent (DA) and Co-Orbital (CO) ASATs. The development of these weapons offer the PRC the means which to destroy with high likelihood adversary satellites. Additionally, they also act as a deterrence capability that can be leveraged to achieve political objectives.
- Electronic Warfare (EW) SATCOM/GPS jammers. These weapons allow the PRC to impact key U.S. capabilities and dependencies with non-lethal effects. These are difficult to detect and attribute, and cause U.S. forces to react to mitigate the impact, which takes time and resources, slowing the pace of battle, a key force multiplier for the U.S.
- High- and low-energy lasers and high-powered microwave weapons. These weapons offer the PRC the capability to achieve a range of impacts on targeted satellites, from disruption and degradation, to destruction. This gives the PRC various attack options to achieve the desired effect which are difficult to detect and attribute, as well as difficult to consider attacks that are escalatory in nature.
- Space-Object Surveillance and Identification systems (SOSI). By expanding and improving its SOSI network, the PRC will be capable of more accurately tracking and targeting space assets, a key aspect of SSA.
- Computer Network Attacks (CNA). Space systems are just as vulnerable to network attacks as any other network. Because of the relative isolation of on-orbit systems, CNA is typically the easiest method in which to attack space systems and their ground networks.

1. Threat Areas

Thus, the PRC seems to be putting substantial effort into a range of development activities aimed to counter U.S. capabilities and dependencies on space-based systems. Of these, four are of immediate concern to me, and will be discussed in more detail.

a. GPS Jamming

In many ways, GPS jammers can be considered the entry level or "first tier" counter-space capability. Most nations and many non-state actors have acquired GPS jammers and actively use them in military operations. These systems are readily available, easily procured, and easily manufactured with relatively little experience or knowledge needed. In fact, instructions for building GPS jammers can be found on YouTube. Now the effectiveness of these homemade jammers is debatable, it serves to highlight that almost all state and non-state actors have some level of counter-space capabilities. Of more concern to the U.S. are the military grade GPS jammers, which can be purchased from various manufactures, to include companies in Russia, China, India, and many more. As an example, one marketed hand-held Russian jammer "can deny access to GPS out to 50 miles; a slightly larger version can jam up to 120 miles" (Garino and Gibson 2009, 276). While the effectiveness of such jammers depends on many factors, the weak signal of GPS makes it susceptible to jamming, especially in close proximity to jammers. Thus, it does not take allot of effort to degrade the GPS signal.

The impacts from GPS jamming are fairly specialized and depend in many ways on the level of operations. Army forces at the tactical level are typically the least effected by GPS jamming because they are operating on the terrain and typically have some knowledge of the battle space. Army accuracy requirements at this level of operations are typically less restrictive, which significantly reduces the dependency on PNT. For example, direct fire forces like infantry, armor, and mechanized infantry can physically see the adversary they are fighting, thus they are relatively unaffected by GPS jamming once in combat. Though loss of GPS would likely have some negative impact on the speed of maneuver, and slow force movement due to positional uncertainty and the resulting delays in BMC2, it can pretty much be ignored during combat. When looking at

the overall context of the campaign, where large periods of non-combat are included, than we can expect to see more effects from GPS degradation on measures of effectiveness like length of battle and number of casualties. Indirect fire systems like Artillery will be more impacted, especially when using GPS guided munitions. These impacts can be partially mitigated by using non-GPS aided munitions and forward observers to direct fire, but this will induce error, increase the number of salvos, decrease effectiveness, and decrease the pace of battle: all of which will impact overall combat effectiveness. Aviation, intelligence, and logistics forces will be even more impacted because these forces are dependent on PNT for efficient execution of their mission sets. For other organizations the problem faced by GPS jamming is even more significant.

Other organizations like the Air Force and Navy will be significantly impacted by GPS jammers, especially in the context of their contribution of combat power in support of the ground force. Because of the characteristics of signal propagation, GPS jamming range increases with altitude. Thus, for higher altitude system like Air Force Bombers, and long range fires like Navy cruise missiles, the GPS jamming range can be significant. Couple this impact with the dependency of modern aircraft, weapons, and other deep strike systems on GPS, and we have a situation where GPS jamming can significantly limit the effectiveness of the strategic deep strike capabilities of the US. Unfortunately, the military has become dependent on deep strike capabilities to support forward deployed forces, and this dependency is expected to grow as the future force downsizes. As the new AOC states, the Army will depend on more of these capabilities to provide the necessary combat power to achieve overmatch. If the effectiveness of deep strike capabilities can be mitigated through adversary use of GPS jammers, then the ability of forward deployed forces to generate overmatch is put at risk. But once again, there is currently no means to quantify this impact, thus no means to evaluate when that transition may occur, and thus, no way to effectively plan for it.

b. SATCOM Jamming

SATCOM jammers can be considered the “second tier” of counter-space capabilities. While SATCOM jammers are slightly more complex than GPS jammers, the

only significant technological advancement needed to develop and employ SATCOM jammers is the ability to track and target a specific communications satellite, and then, having the needed pointing accuracy of the transmitter, put enough power on the target to jam its uplink. None of these technologies is considered cutting edge, but the difficulty in integrating them into a single SoS does provide enough of an obstacle to preclude a large number of adversaries from pursuing these counter-space capabilities. Additionally, because the United States uses such a large amount of SATCOM, hosted by numerous providers on both commercial and military satellites, and using all bands from narrow to protected bands, it is difficult for adversaries to achieve success. In order to achieve the desired impacts to U.S. operations, an adversary would need to develop and field a large number of these systems and employ them simultaneously.

The impacts from SATCOM jamming are again fairly dependent on the level of operations. Like with GPS, Army forces at the tactical level (BN and below) are typically the least affected by SATCOM jamming because they typically communicate with line-of-site HF communication systems, which do not rely on satellites. Thus, over short periods of time, SATCOM jamming has fairly limited impact on combat operations. But as we move above the Battalion level, and consider longer periods of conflict, the impact of SATCOM jamming on Army organizations becomes more apparent, especially at the operational and strategic level of war.

At these levels, impacts to SATCOM can significantly restrict the flow of information, especially the BMC2 and SA information between higher and lower Army echelons that is necessary to maintain the high operational tempo of combat forces which has given the U.S. its tactical advantage. As SATCOM jamming increases in quantity and duration, U.S. forces should expect a steady degradation of combat effectiveness. This degradation is primarily due to a lack of information, which induces greater uncertainty with regard to the USs understanding of the OE, and can increase the time needed for the U.S. to execute its decision making process. Additionally, the ability of forward deployed ground forces to pass and request strategic fires and deep strike capabilities may be hindered, which again will negatively impact combat effectiveness of ground forces who rely on this combat power to achieve and maintain operational overmatch. Thus, over

time, SATCOM jamming can potentially reduce the combat effectiveness of U.S. forces to a point in which the Army's ability to win is put at risk. In other organizations, like the Air Force and Navy, the impact of SATCOM jamming is again much more significant.

Unlike the other services, the Navy relies on SATCOM to provide almost all of its SA, BMC2, and intelligence needs. The Navy is always deployed, to areas where there is no terrestrial communication solution, and therefore, any degradation to SATCOM links due to adversary counter-space activities will have a negative impact on the effectiveness of Navy forces. Without SATCOM, Navy groups operating at sea will be forced to reduce their operational tempo due to a significant increase in uncertainty. Like we saw with ground forces operating in a degraded GPS environment, the Navy would be forced to slow its pace of battle to conduct the necessary reconnaissance activities needed to fill the gaps that would have otherwise been provided through SATCOM. Because of this, a larger portion of the Navy's available combat power would need to be diverted to meet its own requirements, and thus, not be capable of supporting the ground force. This is yet another example of how counter-space activities can reduce the combat power contribution of supporting forces to the ground force, which relies on the Navy's contribution to achieve operational overmatch.

SATCOM jamming can impact the Air Force in a few ways, all with varying impacts on the Air Forces' ability to support ground operations. War planes operating in support of combat operations will typically have HF comms with the units they are supporting and thus, are not as impacted by SATCOM jamming. However, the majority of the higher level Air Force operations are heavily dependent on SATCOM, especially at the operational and strategic level. The foundation of Air Force operations revolves around the daily execution of the Air Tasking Order (ATO). This planning process is extremely efficient, yet it is also heavily dependent on SATCOM to gather information and to disseminate orders. Almost the entire intelligence tasking and collection network relies on SATCOM to request and provide the desired intelligence products needed to execute the targeting process effectively, as well as to conduct the BDA following strikes. Degradation of SATCOM could impact the understanding of the OE, resulting in a less effective targeting and assessment process as well as a slower operational tempo.

Another significant impact to Air Force operations due to SATCOM jamming is the impact to its fleet of UAVs, which depends on SATCOM for their operational control. UAVs are an incredibly important capability that provides a significant contribution of combat power to the ground force by providing additional capability to collect intelligence, as well as to provide fires in support of combat operations. However, these deep strike capabilities can be highly sensitive to jamming, which can reduce the effectiveness of UAVs and potentially negate their contributions to combat power.

National command and control will also be vulnerable to SATCOM jamming. While the majority of these communications would likely be conducted over protected communication bands, we know that the throughput of these systems is extremely limited, allowing only the most import and critical information to be passed. Thus, there will be a significant amount of information that can potentially be negated due to adversary SATCOM jamming. Because this information contributes to an operational commanders' understanding of the OE, reduction in the throughput of these links can and will have an impact on metrics of operational effectiveness. Additionally, SATCOM jamming can also potentially impact the ability of the USG to execute its oversight and control of military operations over long distances. This reduced control can induce operational uncertainty, which may result in a slower decision making process.

According to the new AOC, the Army of the future can expect to be rapidly deployed into areas where it will have little to no infrastructure support and likely be outmanned, out gunned, and out resourced. To achieve and maintain operational overmatch against these odds, the Army will be highly reliant on support from the Navy, Air Force, and National Strategic capabilities to provide the necessary combat power. If the effectiveness of Navy, Air Force, and national capabilities can be mitigated through adversary use of SATCOM jamming, then the ability of forward deployed forces to generate overmatch is put at risk. But once again, there is currently no means to quantify this impact, thus no means to evaluate when that transition may occur, and thus no way to effectively plan for it.

c. Direct Energy Weapons

Direct Energy Weapons can be classified as advanced counter-space capabilities and occupy what I will call the “third tier” of counter-space capabilities. These are truly technologically advanced capabilities and prove to be significant obstacles to even the most determined adversary. Non-state actors and the majority of nation states will not have these capabilities, primarily due to the extreme complexity, cost, and resource requirements needed to develop and field such systems. Direct Energy Weapons are therefore reserved for just a handful of the largest and most technologically advanced countries and can be classified into three primary weapon types: lasers, RF, and Particle Beam. These all have varying levels of capabilities and potential impacts, with complexity ranging from advanced technology, as we see with lasers, to the nearly theoretical realm of Particle Beam Weapons. Of these three, lasers are the most common and currently the only direct energy weapon in operational use today. Consequently, I will only be considering lasers in this dissertation.

Lasers are dual use technologies that prove to be difficult to mitigate. Low power lasers are routinely used for range finding, which is essential for maintaining a nation’s Space Situational Awareness (SSA). Thus, it is difficult to classify lasers as weapons until they are used as such, and even then it is often difficult to detect and attribute this to any specific adversary. Low power lasers can easily be used to disrupt U.S. satellite imagery by “dazzling” our sensitive sensors. While laser dazzling is typically non-destructive, it does interfere with the United States ability to maintain its informational advantage, which can have negative impacts on combat operations. This problem is further complicated by the fact that laser counter-space capabilities can be increased by increasing the output power. Thus, through the technical expansion of current laser capabilities, an adversary could be capable of developing systems that are far more capable, with potential impacts including everything from disruption through dazzling, to degradation and potential destruction of targeted satellites. Luckily, the effects of lasers are generally restricted to satellites at low altitudes like LEO. Satellites at higher altitudes like MEO and GEO, and more protected due to the laser scattering and dissipation effects that reduce the effectiveness of the laser at greater ranges.

The difficulty in mitigating the potential impacts from lasers is threefold. First, it is difficult to classify reversible and/or temporary impacts as attacks, especially enough to justify a kinetic response. Second, it is often difficult to prove that an attack even took place, and even more difficult to attribute the attack to a specific adversary. Third, given that the first two are addressed, we often do not even possess the capability to attack the source. For example, the PRCs laser range finding "network consists of five fixed stations located at space observatories in Shanghai, Changchun, Beijing, Wuhan, and Kunming. At least two mobile systems are also available" (Heginbotham et al. 2015, 246). So, even given a destructive attack on U.S. systems that we can positively attribute to an adversaries laser, what could be done about it? All of these systems are located in areas of mainland China that are extremely difficult to target, and the mobile systems would be nearly impossible to target. Obviously, we would need to reciprocate, but how? In the case of China, the lasers themselves are likely too difficult to attack, and thus, they would likely continue to impact U.S. systems. Thus, we find ourselves in a situation where we can expect to be continually impacted by these systems and should expect to operate with degraded collection capabilities in any conflict with the PRC. Even if an adversary chooses not to employ its lasers as weapons, they will "still be an important element in the counterspace 'kill chain,' providing data of sufficient precision to target U.S. satellites with other weapons" (Heginbotham et al. 2015, 247). Thus, these systems pose a threat in all roles and must be accounted for in operational planning.

The potential impacts of adversary use of lasers on combat effectiveness are again fairly dependent on the level of operations. The primary target for non-destructive lasers will be ISR assets, and thus, the intent of adversaries will likely be to blind U.S. collection assets in an effort to mask adversary actions and to induce uncertainty into the U.S. decision making cycle. This is less effective the closer to the forward line of troops we get, and thus, Army forces at the tactical level (BN and below) are again the least affected. Tactical forces do not rely on current high resolution imagery as much as higher echelon planners do because they typically have local collection assets that maintain contact with the adversaries' forces. But as we move above the Battalion level, and consider longer periods of conflict, the impact of adversary use of lasers can become

more apparent, especially at the operational and strategic level of war. Once we start to consider lasers at higher power levels, where they can damage/destroy U.S. assets, the potential impacts become much more severe. In this case, all satellites at LEO become potential targets, significantly complicating potential mitigation plans.

Decision makers depend heavily on space-based ISR to support operational planning and lasers can significantly restrict the availability of these products. Luckily, due to the large number of potential commercial and government sources of ISR, it is unlikely that an adversary could ever completely negate the United States' access to space-based collection. But even if this is true, adversaries can still negatively impact U.S. operations by reducing the availability of ISR. Doing so would induce operational delays as decision makers wait for key information, significantly slowing the United States' operational tempo and thus, reducing tactical advantage. As adversary lasers increase in quantity, duration, and capabilities, friendly forces should expect a steady decrease in collection capacity and a degradation of combat effectiveness, especially over longer periods of conflict. This would again introduce uncertainty with regard to understanding of the OE and would increase the time needed for the Army to execute its decision making process. In other organizations, like the Air Force and Navy, the impact of laser weapons will be similar. Thus, over time, laser weapons could reduce the combat effectiveness of U.S. forces to the point where we put our ability to win at risk.

d. ASAT Weapons

Anti-Satellite weapons can be classified as extremely advanced counter-space capabilities, and occupy what I will call the "forth tier" of counter-space capabilities. These systems cannot be procured, and are extremely difficult to develop and manufacture, requiring advanced expertise in space, targeting and tracking, launch, ballistic missiles, intercept technologies, propulsion, and exo-atmospheric maneuver. The technological requirements needed to develop these systems are only possible within a few of the largest and most technologically advanced countries with well-established space programs and substantial resources in both time and money. ASAT weapons can be classified into three primary weapon types, Direct Ascent-Low Earth Orbit (DA-LEO),

Direct Ascent-Geostationary Orbit (DA-GEO), and Co-Orbital (CO). These all have varying levels of capabilities and potential impacts, as well as overall complexity. Of these three, DA-LEO ASAT weapons are the only ones which have been operationally tested, but all three have been demonstrated sufficiently enough to consider them operationally feasible. Because of the potential threat of these systems we must consider all of them as operational. We can expect advanced adversaries to maintain relatively small quantities of DA-ASAT weapons, as well as 1–2 prototype GEO and CO ASAT weapons. Thus, all three of these systems will be considered in this work.

DA-ASATs (LEO) are the most well-known and established ASATs currently in operation. These systems are capable of being launched from the ground, ships, or aircraft, and intercepting a target satellite in LEO. The United States and Russia have both had this capability since the 1980s, with both countries testing them multiple times during the height of the cold war. These weapons fell out of developmental favor after both the United States and Russia agreed that such weapons were counter-productive to the safe and secure access to space by both parties. While the weapons were maintained in the inventory, all significant development of these systems was halted. It was not until the January 2007 launch of a Chinese DA-ASAT that the U.S. reinvigorated its counter-space R&D efforts. This launch exposed the threat to U.S. systems, and "proved that China can range critical U.S. space systems in low Earth orbit, such as meteorological and electro-optical surveillance satellites" (Tellis 2014, 1). It is expected that the PRC has a handful of these systems, and thus, for this work, we will assume that an adversary is capable of completely destroying any U.S. asset in LEO. While DA-ASATs (LEO) are technically the only type of ASAT weapons that can be considered operational, there are other less mature systems capable of impacting U.S. operations as well.

DA-ASAT (GEO) weapons are a logical evolution of DA-ASAT (LEO) weapons. By increasing the weapons range an adversary is able to increase the number of potential targets, to include high value national systems typically found in MEO and GEO. By achieving the capability to attack satellites in GEO, an adversary can now put at risk all U.S. assets, regardless of their orbits. The May 2013 launch of an unknown PRC system was suspected to be a DA-ASAT (GEO) test, and if true, would prove that the PRC has

the capability “to place a kinetic kill vehicle on a trajectory to deep space that could reach medium earth orbit (MEO), highly elliptical orbit (HEO), and geostationary Earth orbit (GEO)” (Weeden 2014, 1). This is a significant capability, and one that the U.S. may or may not be capable of accounting for. Even though this capability has not been operationally tested or acknowledged, most planners now expect that the Chinese have this capability. Consequently, we must consider the potential impacts of this weapon on operations in future planning. While the PRC likely only has a few of these weapons, we must assume that they are capable of completely destroying any U.S. asset out to GEO.

Co-Orbital ASAT (Co-ASAT) weapons more closely resemble satellites than weapons, and for good reason, a CO-ASAT is a satellite. The only difference is that a CO-ASAT was designed to impact satellites, and thus, be a weapon. Technically, any satellite that has the capability to maneuver could possibly be used as an ASAT. And though it requires some detailed knowledge of the space environment and the target, the technology itself is not nearly as complicated as DA-ASATs. Any country that has an active space program already has all the technology needed to produce and use these systems. And while they have significant legal and treaty implications, specifically revolving around the topic of the weaponizing space, the fact that such systems are difficult to discern from other satellites makes it extremely difficult to classify them as weapons. Because of the benefits and flexibility such systems provide, China has “embarked on a programme to develop a co-orbital anti-satellite interceptor, launched from Earth into a temporary parking orbit from which it then manoeuvers to attack its specific target” (Tellis 2007, 54). Again, even though this system has not been operationally demonstrated, we must assume that the capability exists, and thus, we must consider all potential effects that such a system can have on U.S. operations.

2. Vulnerabilities

Because “PLA writings emphasize the necessity of ‘destroying, damaging, and interfering with the enemy’s reconnaissance … and communications satellites,’ suggesting that such systems, as well as navigation and early warning satellites, could be among the targets of attacks designed to ‘blind and deafen the enemy’” (DOD 2014a, 32), the United States must take a more proactive role in mitigating the risk it faces when

considering the uncertainty of future combat environments. Yet, the focus of these efforts should align with the potential threats, which as discussed, are based on the perceived vulnerabilities. Thus, I will focus the majority of analysis addressing the potential impacts on U.S. SATCOM, ISR, and PNT.

a. U.S. SATCOM

As adversaries develop more and better SATCOM jamming capabilities, we can expect the access to critical information links to be put at greater risk. Couple this with the increase dependency on SATCOM by U.S. forces as we transition under the new AOC, as well as the proliferation of SATCOM jamming technologies to new and emerging adversaries, and this threat is only compounded. What this means for the warfighter is that as jamming increases, the overall availability and flow of information will decrease for most users due to the re-allocation and re-prioritization of available bandwidth. As the jamming surpasses the availability of redundant communications, lower priority users will begin to see a significant portion of their bandwidth re-allocated to higher priority users. Thus, while all units will likely incur a reduction in throughput, lower priority users will see a significant decrease in throughput, likely seen as less access to information. While this may seem like an acceptable mitigation plan, understand that almost all commanders, at almost every echelon of operations, have become accustomed to having access to a large amount of information and bandwidth. To think that the sudden decrease in access would occur without impact would be foolish.

Work done by Lindquist (2004) was an example of an early attempt to capture the impacts of degraded communications induced by adversary use of Electronic Warfare (EW) assets on the combat effectiveness of the Future Combat System (FCS), a heavily informationally dependent SoS architecture that was later scraped for cost overruns and complexity. While his work is fairly low resolution, it is one of the first attempts to try to quantify the operational impacts of degraded communications. In his work, Lindquist (2004) shows that “when communication range is degraded more than 25 percent, the result is nearly three times the expected number of FCS casualties” (xxi). In addition to this primary finding, he also makes another observation that has nearly as much

importance when addressing the threat from operations in a D3SOE. Lindquist observed that as communications are degraded, the length of battle is increased, which intuitively makes sense. As degradation increases, uncertainty also increases, and the natural impact of that uncertainty is a slower pace of battle as leaders attempt to address the uncertainty, and typically, there is a strong correlation between this delay and an increase in casualties. Thus, as Lindquist (2004) states, “even small delays (latencies greater than one minute) and constraints on network throughput can increase the Future Force casualties and the duration of battle” (i). While the end state of his simulations typically favored the FCS force, regardless of the level of degradation, he found that “the cost of that victory [in lives and time] depends significantly on effective communications” (Lindquist 2004, v). Some of his key takeaways from this work is that it was advantageous for the adversary to employ its EW weapons early in the battle, the earlier the better, and that “enemy electronic warfare assets must not be underestimated and should be a focus of any pre-engagement intelligence activities” (Lindquist 2004, xxii). Additionally, that degradation of communications range, throughput, and latency all negatively impacted the combat effectiveness of friendly forces, typically observed in combat effectiveness as number of casualties and length of battle. Although his work addresses a specific problem faced by a specific system, it supports the claim that operations in a D3SOE will have impacts to combat effectiveness.

b. U.S. ISR

While the threats to U.S. ISR assets are different from those of U.S. SATCOM, the potential impacts are similar, though far more apparent for two primary reasons. First, the U.S. has far fewer ISR assets, and thus, the loss of any capability will have a larger impact on the overall availability of ISR collection. Second, there are more potential threats to U.S. ISR assets than to U.S. SATCOM, and the risk is much greater. This is due to the combination of the orbital altitudes of ISR assets, which are much easier to attack at LEO, and the fact that adversaries continue to make advances in ASATs, specifically DA-ASATs and Lasers. Thus, we can expect the access to U.S. ISR collection assets to be put at greater risk in the future. What this means for the warfighter is that as combat escalates, and the adversary begins to use Lasers and DA-ASATs

against U.S. ISR assets, the overall availability to current high resolution imaging will be significantly reduced. Coupled with the dependency of ISR data to be moved via SATCOM links, and one can see how adversary simultaneous attacks against ISR assets as well as U.S. SATCOM can compound the potential threat.

And as we saw with SATCOM, the availability of ISR collection capabilities will be restricted to only the highest priority users, typically at the national and strategic levels. This significantly reduces the availability of current ISR data to the tactical users, who often rely on this information to make more informed decisions as the battle progresses. The lack of current and timely ISR data will induce a high level of uncertainty into the COP, and thus, slow the speed at which the U.S. executes tactical operations as tactical commanders are forced to seek out other means in which to address informational gaps. As we saw with communications, the unrealized risk here lies with the fact that commanders at almost every echelon of operations have become accustomed to having access to a large amount collection data. Thus, as we saw before, the adversary "pulling the proverbial rug" out from underneath U.S. commanders will not happen without some operational impacts.

Work done by Treml (2013) was an example of an early attempt to quantify the contributions from ISR on combat effectiveness. In his work, Treml (2013) shows that "the improved UAV sensor increases the situational awareness of all BLUE agents, which leads to a higher BLUE survivability and lethality" (74). As SA is developed, leaders will have a better understanding of the OE, and thus, have the information needed to make faster and more informed decisions. Another key finding by Treml (2013) was that the level of "communication and data exchange for fire coordination, targeting information and allocation" had direct impacts to metrics of combat effectiveness (19). Like Lindquist, Treml's work links combat effectiveness to communications, information sharing and SA, and in his conclusion, Treml (2013) states that "the most significant factors for decreasing BLUE casualties are better sensors on the GCV. Better sensors enable the GCVs to detect, report and engage the enemy faster and to increase the situational awareness of all BLUE agents" (86). Again, while this only holds true to the scenario he developed in the context of the problem he was investigating, his findings

support the work of others. Some of the key takeaways from his work suggest that "improved sensor quality of one system combined with network capability can greatly enhance the performance of the whole force according to casualty expectance and battle duration" (Treml 2013, 88). This again highlights the importance of collection capabilities, as well as the necessity to disseminate that information throughout the force.

Another key body of work was done by Soh (2013), and differed from Treml' s work in that it attempted to capture the impacts to combat effectiveness through the introduction of new capabilities, specifically the addition of ISR collection assets like UAVs. Her work focused on the impact that ISR systems have on SA, and how an increase in SA can positively impact measures of operational effectiveness like survivability and force protection. Her work is rooted in the SE process, and uses MBSE to drive the conceptual development of emerging UAV systems. In the context of my work, I consider this a mitigation strategy, in which we can attempt to overcome adversary counter-space activities through the use of additional capabilities. In her work, Soh (2013) shows that "outgoing communication accuracy of Infantry and Ground Combat Vehicles (GCV) sensor classification accuracy of Unmanned Ariel Vehicles (UAV), the number of UAVs, as well as UAV latency to have the most influence on situation awareness" (xvi). This captures two aspects of what I am attempting to address. First, that degradation in the communication capabilities of collection assets will have a negative impact on combat effectiveness. This supports my earlier claims that degradation of collection assets, regardless if the degradation is aimed at the collection assets directly or at the communication paths the information takes, will have a negative impact on combat effectiveness. Second, increasing the number of ISR collection assets or their capabilities will have a positive impact on combat effectiveness. Thus, the introduction of additional ISR collection assets is a viable mitigation technique for countering adversary counter-space activities. Some of his key takeaways from this work is that "number of the UAVs has a significant influence over the building up of situation picture and its comprehensiveness" (Soh 2013, 65). Thus, the more collection assets we have, and the better their capabilities are regarding accuracy and speed of information dissemination, the faster and better our understanding of the OE will be.

c. *U.S. PNT*

Because GPS jamming technology has proliferated to such an extent, GPS jammers have become expected in modern combat operations. All current and potential adversaries are expected to possess GPS jammers in some quantity at various levels of capability, and because of this, the U.S. military has made some progress in mitigating the impacts that these systems have. While there are still areas where GPS jamming possess a credible threat, for the most part these impacts are limited to niche areas like network timing disruption, deep strike fires accuracy, and weapons guidance, all of which are currently being resolved. Nonetheless, adversary use of GPS jammers can and will have an effect on operations. At the highest levels, the primary purpose of GPS jammers is to induce uncertainty into the COP, and thus, to slow the speed at which the U.S. executes tactical decision making. In an environment where GPS jammers are present, the warfighter will be required to put forth more effort to ensure accurate movement and targeting. While the length of this delay is highly dependent, there will be some amount of delay, and though it may seem fairly negligible, these small perturbations in decision making can have a much larger cumulative effect on the operation as a whole, potentially reduce the overall advantage that information superiority brings the U.S. military.

Unfortunately, it is not just the PRC we should be concerned with. All state and non-state actors recognize the United States' dependency on space assets as well as their vulnerabilities. While only a handful of potential adversaries are capable of significantly effecting U.S. space capabilities, all adversaries, in one way or another, are working to mitigate U.S. capability.

C. THE "NEW" OPERATIONAL ENVIRONMENT

In fact, the only specifics of the new AOC deal with its unspecific nature, no longer do we know who or how we will be fighting, what environment we will be fighting in, or with whom. In the future, the Army will "possess the ability to operate dispersed over wide areas because they are able to integrate intelligence and operations to develop *situational understanding through action* while possessing the *mobility* to concentrate rapidly" (U.S. Army 2014b, iii). Figure 113 shows the AOC logic chart.

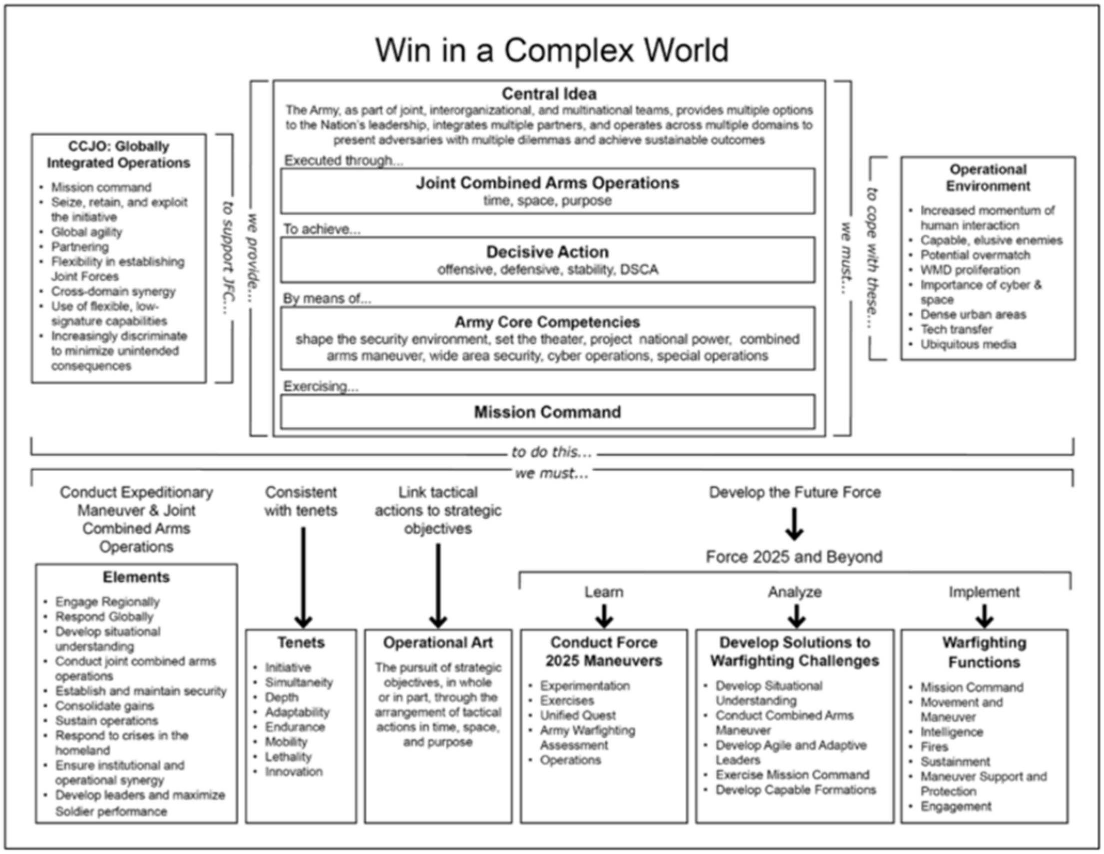


Figure 113. Win in a Complex World Logic Chart.
Source: U.S. Army (2014b, vi).

As shown in Figure 113, the problem of winning in a complex world is a difficult one. This scenario is equivalent to studying to pass your Ph.D. oral examinations when the topic, the department, the location, the language, the committee members, or the time that the test will be given are unknown. This is a tall order and requires a solid understanding of not only the potential threats of the future, but also of our own capabilities and vulnerabilities. The problem of planning for an uncertain future is even further complicated by the fact that as the Army attempts to plan for an infinite set of potential threats and OEs, our adversaries do not. Potential adversaries have a much clearer and more finite understanding of their threat, the United States, and thus, do not suffer from the same level of uncertainty. “Countries such as China will continue seeking to counter U.S. strengths using anti-access and area-denial (A2/AD) approaches and by employing other new cyber and space control technologies” (DOD 2014b, 6). Regardless,

the United States must face this challenge in a resource restricted environment, where the adversary holds many of the advantages, and prepare the force to, as the AOC states, "Fight and Win in a Complex World."

D. EMERGING MITIGATION STRATEGIES

In the 2010 National Space Policy, the President of the United States directs the Secretary of Defense to "ensure cost-effective survivability of space capabilities, including supporting information systems and networks, commensurate with their planned use, the consequences of lost or degraded capability, the threat, and the availability of other means to perform the mission" (The White House 2010, 13). While this policy statement gives no specifics regarding how to accomplish the tasks, it does give a clear end state, which gives subordinates a clear understanding of the goal with the flexibility to address it as needed. Policy serves to give clear guidance to subordinates while providing the flexibility to investigate potential solutions without constraints and limitations. Take this policy as another example: "our military and intelligence capabilities must be prepared to 'fight through' a degraded environment and defeat attacks targeted at our space systems and supporting infrastructure. We must deny and defeat an adversary's ability to achieve its objectives" (DOD 2011a, 11). The flexibility of the statement gives subordinates enough space to figure it out without overly constraining potential solutions.

1. Doctrine

Of all the potential areas of mitigation, emerging policy is making the most progress with regard to preparations for operations in a D3SOE and the establishment of mitigation strategies. Because policy includes top-level directives (Strategic) which flow down to drive TTP (Operational) development, TTPs often lag behind the establishment of policy. Because of this, the majority of all emerging mitigation strategies currently being considered are based on directives from the highest levels of National Policy, like the National Space Policy. These documents clearly articulate the President's desire to protect our key capabilities, stating that "we will move toward less complex, more affordable, more resilient systems and system architectures and pursue a multi-layered

approach to deter attacks on space systems while retaining the capabilities to respond should deterrence fail" (DOD 2014b, x). Most emerging mitigation policy trends tend to address this statement by focusing on four broad concepts of mitigation: graceful degradation, resiliency, disaggregation, and cooperation.

a. Graceful Degradation

To win in a complex world, the overarching goal of the AOC, the Army must "assure uninterrupted access to critical communications and information links (satellite communications; position, navigation, and timing; and intelligence, surveillance, and reconnaissance) when operating in a contested, congested, and competitive environment" (U.S. Army 2014b, 32). This is concerning to me because on one hand, we are told that to win the United States must assure uninterrupted access to space based systems and capabilities in a D3SOE. On the other hand, we have also been told that adversaries "can and will" degrade and interrupt our space-based capabilities through the use of counter-space capabilities. Thus, we have two definitive policy statements that directly contradict one another. The adversary will interrupt our access to space-based capabilities, and these capabilities must not be interrupted for the U.S. to win. Luckily, I am not alone in identifying this contradiction of policy, and a relatively new way of looking at this problem is emerging within the space community, which is the concept of graceful degradation. In this concept, adversary counter-space activities will be expected to be somewhat effective at degrading our capabilities. Likewise, our mitigation strategies will also be somewhat effective at mitigating the impacts. Thus, we expect to see a gradual degradation of capabilities as adversaries increase the use of counter-space activities, somewhat mitigated by the gradual increase in United States response. The key difference is that by loosening the requirements away from the definitive must statements seen in current doctrine, we allow for enough flexibility in requirements of emerging doctrine to support the exploration of alternative mitigation strategies, ones that may not prevent an attack but are capable of reducing the impact.

b. Resiliency

Because of the rapidly increasing threat and the inability of the United States to effectively counter it, a key emergent term that has quickly gained support from the DOD is the concept of resiliency. Resiliency is defined as “the ability to absorb strain and preserve (or improve) functioning despite the presence of adversity (both internal adversity … and external adversity)” (Sutcliffe and Vogus 2003, 3). Simply put, resiliency is the ability of a system to maintain its operational capabilities regardless of friendly and enemy activities, across a wide range of possible OEs. The importance of resiliency in an era when the United States no longer holds a commanding technological advantage should be apparent. As stated in the 2014 Quadrennial Defense Review, investments in current and future technology acquisitions must evolve to provide more resilient systems and architectures for the future force to preserve the operational capacity of U.S. operational forces (DOD 2014b). In this strategy, policy would call for the use of technology, TTPs, and Army modeling to focus on improving the resilience of U.S. systems, and thereby reducing the impacts that potential attacks could have on U.S. operational effectiveness. U.S. Army TRADOC identified a set of four concepts of resiliency in its 2014 AOC that attempt to clarify in policy how resiliency can be achieved. These concepts include: the development of “resilient and hardened systems that degrade gracefully under attack rather than fail catastrophically”; “redundant means for communication and coordination”; “realistic joint training under degraded communications conditions”; and the pursuit of “a mix of technological and non-technological solutions to build sufficient redundancy and adequate reliability of systems.” Unfortunately, while the U.S. Army understands the value of space-based capabilities, as well as risk to its space-based capabilities from adversary systems, its implementation of the concepts of resiliency has been minimal.

c. Disaggregation

Another emerging means by which to mitigate the operational effects from operations in a D3SOE is through the concept of disaggregation by system. Simply speaking, disaggregation by system is the breaking down or decomposition of larger,

more complex space systems into smaller and simpler systems. While these smaller and cheaper systems are typically less capable, the loss in capability can be partially regained through the acquisition of an increased quantity. The advantage of disaggregation is that the overall risk due to the loss of any specific system is significantly reduced, and allows the Army to better "evade enemy attacks, deceive the enemy, and achieve surprise" (U.S. Army 2014b, 18). By disaggregating our space assets into numerous smaller satellites, we can disperse them, and increase the difficulty of our adversaries to track and target them, as well as reducing the operational gain achieved by doing so. To demonstrate the benefits of disaggregation by system, consider the loss a single WGS communication satellite operating over the Pacific. This loss would have a significant impact to operations in Theater, potentially reducing the communications capacity in theater by up to 33%. However, if this same capability was to be spread out among five smaller satellites, the loss of any single satellite would only reduce the communications capacity by 7%, a vast improvement.

A variation of disaggregation by system is the concept of disaggregation by capabilities. Rather than building smaller versions of the same satellite, this concept focuses on spreading the capability out to other system alternatives. The key focus here is to enhance resilience through the development of "mission-effective alternatives, including land, sea, air, space, and cyber-based alternatives for critical capabilities currently delivered primarily through space-based platforms" (DOD 2011a, 11). By spreading the key capabilities out to other alternatives, to include satellites and other non-space systems like UAVs and near-space platforms, we can disaggregate the capability throughout the domain as well as into other domains, like air and near-space. Disaggregation by capabilities results in a decreased risk from the loss of a single system, as well as gives the adversary a more difficult, cross-domain targeting problem, which they may or may not have an available solution.

It is for the reasons previously stated that the concepts of disaggregation have quickly become the buzz work within the space acquisitions communities. While the amount of capability lost due to employing the concepts of disaggregation remain unclear, especially with regard to the costs associated with the development and

acquisitions of these systems, it is easy to see why the concept of disaggregation has been receiving so much attention. Through disaggregation we can reduce risk and operational impacts while increasing the difficulty of the adversary to employ its space-control weapons…a win-win. Given the threat we currently face, and the loss of capabilities we have been told to expect in conflict, I believe that most commanders would be willing to trade off capability through disaggregation to ensure that the impact from system loss in conflict can be mitigated.

d. Cooperation

The final emergent means to mitigate the effects from operations in a D3SOE is through the concept of cooperation. Technically, cooperation is just another method disaggregation by capability, but focuses on reducing risk by spreading capability requirements out to other systems, specifically to commercial as well as foreign systems. Through cooperation the risks to military operations are reduced by spreading out space dependencies among commercial entities and partner nations through contracts, shared usage agreements, and treaties. By moving away from a single satellite provider, we spread that requirement out between U.S. systems, commercial systems (U.S. and foreign), and partner nation systems. Cooperation can multiply the effects of resiliency through disaggregation of capability, but with less loss in capability as seen in disaggregation by system because they are typically comparable to U.S. national systems.

2. Technologies

Counter-space systems present a significant threat to the United States' freedom of maneuver, and "to prevent enemy overmatch, the Army must develop new capabilities while anticipating enemy efforts to emulate or disrupt those capabilities" (U.S. Army 2014b, 11). In addressing this concern, numerous potential technological solutions have been considered to address the gaps identified in policy, yet the majority of these strategies focus on the system, and attempt to mitigate the threat primarily through resiliency in design, i.e., engineering and redundancy. Thus, most technological mitigation strategies tend to coalesce around four areas of research: the hardening of components from damage and component redundancy, system backups and spares, anti-

jam modulation technologies, and laser communications. While these technological mitigation strategies succeed in addressing mitigation through resiliency, they fail to fully account for other mitigation strategies like disaggregation. To be successful in mitigating the threats posed by counter-space weapons, the Army must consider all areas of potential mitigation, not just system level technological solutions, and "invest in and deliver future force capabilities to maintain a competitive advantage against increasingly capable and determined adversaries" (U.S. Army 2014b, 24). Fortunately, two emerging technological systems that seem to address both the concept of resiliency as well as the concept of disaggregation are SmallSats and HAAS.

a. Small Satellites (SmallSats)

SmallSats are emerging technologies that look to break the current trend of developing system level resilience through disaggregation of the system. When considering SmallSats, the Army should consider "deploying small affordable, disaggregated hosted payloads, as well as communications satellites that use more responsive, more affordable, space-launch services" (U.S. Army 2014a, 10). Thus, using SmallSats a capability like communications can be disaggregated to a constellation of smaller, less expensive satellites. While the overall capability of the new constellation may be 20–40% lower than the larger satellite, depending on the number of satellites and mission, the overall reduction in risk can be as high as 90–95%. Thus, for a manageable loss of capability, we achieve a huge reduction in operational risk. Unfortunately, the full implementation of SmallSats as potential mitigation strategy has been significantly hampered by the level of uncertainty regarding costs and capabilities. Many of these strategies look to be "very expensive to implement, especially considering the relative low costs of many ASAT systems that can destroy satellites or degrade their functionality in a wartime setting" (Saunders 2015, 8). Regardless, the Army, as well as the DOD has recognized the potential of SmallSats to address the inherent risks associated with large and complex satellites and is actively pursuing research in this area. By focusing more on technological solutions that address resilience through disaggregation of the system, the Army looks to better prepare itself for operations in a D3SOE.

b. High Altitude Atmospheric Satellites (HAAS)

HAAS is an emergent technology that is a perfect example of disaggregation of capabilities, where the capabilities typically provided by a few large and expensive satellites, are disaggregated to other systems in other domains to reduce risk and build resilience. The key characteristics of HAAS that make them such an appealing mitigation strategy is that they operate at high altitudes, sometimes referred to as near-space, occupying the gray area between the Air Domain (0-18km) and the space domain (60km and above) which adversaries have not had to deal with before. By operating in this gray area between the Air and Space domains, HAAS are capable of achieving some pretty significant outcomes. First, they can provide nearly the same capabilities as a space-based platform at a significantly reduced cost. Second, they are recoverable, and payloads can be interchanged and tailored based on the needs of commander. Third, they are deployable, and thus capable of being used in support of tactical operations in disadvantaged areas, or as augmentation when reconstituting lost space systems. Forth, they are at far less risk from adversary attacks than space systems because they operate outside the range of most surface to air weapons, yet below the range of DA-ASATs. Because of these unique capabilities, HAAS have the capacity to be critical combat enablers of the force "when fighting though degraded space environments, while conducting A2/AD operations, operating in austere environments, and when surging forces to theater" (U.S. Army 2014a, 21).

While I believe that HAAS represent the greatest opportunity for taking a proactive step to mitigate the threats faced from adversary use of counter-space weapons, "Army acquisition and S&T communities have been unenthusiastic in pursuing Army space or space-like platforms (once called 'near-space' platforms) such as High Altitude Atmospheric Satellite (HAAS) airframes, believing the responsibility of developing HAAS belongs to the Air Force or other joint agencies" (U.S. Army 2014a, 9). This is unfortunate because the Army (and Marines) is the only force concerned with the impacts on ground operations due to operations in a D3SOE. While the Air Force is concerned with operations in a D3SOE, their perspective is from the Air and Space domains, and the metrics they use to assess impacts do not translate to the ground force. When coupled

with the fact that HAAS primarily serve ground forces, fills no specific Air Force capability gap, operate in near-space which the Army is the proponent for, it is easy to see why the Air Force is unlikely to expend resources on near-space systems.

While SmallSats and HAAS are technological solutions that can support the development of mitigation strategies by building system level resilience, they cannot ensure resilience above the system level, nor can they fully account for the concept of disaggregation. When considering the rate adversaries are expanding their counter-space capabilities, as well as the fact that "technologies change rapidly and transfer easily, the U.S. military will have to accelerate new technologies into the force to maintain its ability to overmatch enemies" (U.S. Army 2014b, 36). Thus, the United States cannot rely solely on mitigation strategies based on system level resilience, and as stated by TRADOC, "the Army's ability to achieve significant leaps in warfighting efficiency and effectiveness requires an understanding of the interaction of technology with changes in doctrine, organizations, training, and other elements of combat effectiveness" (U.S. Army 2014b, 36). To this end, two additional technological mitigation strategies are used in conjunction with the system level technological mitigation strategies to mitigate the impacts from operations in a D3SOE, namely mitigation through partnerships and mitigation through acquisitions.

c. Mitigation through Partnerships

In this strategy, what I like to refer to as mitigation through excess shared capacity, there is an abundance of space systems available at any given time that can be prioritized and allocated as needed. This mitigation strategy relies heavily on the acquisition and use of both partner nations and commercial satellite technologies to augment U.S. national systems. By sharing resources, the United States effectively expands its technological base by increasing the number of available satellites for use, forcing any potential adversary to re-assess the cost-benefit analysis of a counter-space attack. Thus, through excess shared capacity we can increase friendly capability and capacity while sharing the cost and risks among all participating parties.

d. Mitigation through Acquisitions

In this strategy, the United States attempts to mitigate risk through the iterative development of current system technology to acquire newer and more capable systems in the future. Through continuous design improvements, the United States maintains a constant technological development cycle where improved and more capable systems across all space segments are acquired and fielded every few years. Thus, I often refer to it as "mitigation through acquisitions," where we attempt to buy our way out from a threat. This complements mitigation through partnerships by ensuring that the U.S. retains some dedicated space systems that maintain the technological edge for when the use of partner nation or commercial satellites is not a viable solution to meeting key U.S. requirements. While this strategy has been successful at keeping U.S. systems at the forefront of space capabilities, it has done little to thwart any potential threats from counter-space systems.

E. CONCLUSION

The threat posed to U.S. Army operations from adversary space and counter-space activities is not a new vulnerability; in fact, it is well documented throughout most national policy and doctrine and fairly well understood. Almost all organizations understand that "space is vital to U.S. national security and our ability to understand emerging threats, project power globally, conduct operations, support diplomatic efforts, and enable global economic viability" (DOD 2011a, 1). However, understanding the threat is not the purpose of this work. The threat has already been identified, so this work instead focuses on understanding the impacts that this threat has on combat operations.

SUPPLEMENTAL

This dissertation includes two supplemental files, which can be obtained by contacting the Naval Postgraduate School Dudley Knox Library. The first file is the Implicit Model Development Process (IMDP), which formalizes the methodology for expanding traditional Model Development Processes (MDPs) to address External, Seemingly Intangible/Non-Quantifiable (ESINQ) factors and effects when developing models. This contribution is codified in the form of a Microsoft Excel Spreadsheet consisting of 16 tabs, in addition to the nine supplemental tabs needed to address Trade Space Exploration (TSE).

The second file is the Improved Relative Combat Power Assessment Tool (IRCPAT), which is an improved operational decision support tool developed to improve Army planning. The tool provides users an expanded capacity to compare the relative combat power of opposing forces, and to visualize and examine the impacts that external dependencies, ESINQ factors and effects, and external systems have on metrics of operational effectiveness of the ground force. Like its predecessor, the Force Ratio Calculator (FRC), the IRCPAT is codified in the form of a Microsoft Excel Spreadsheet consisting of 12 primary tabs, and two example expansion tabs.

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